# A Feasibility Study for Titanium Recycling in South Africa

by

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*Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Industrial Engineering in the Faculty of Engineering at Stellenbosch University*

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December 2016

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# Abstract


### A Feasibility Study for Titanium Recycling in South Africa



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Thesis: MScEng (Industrial)

December 2016



In this study, the possibility of titanium recycling in South Africa is explored. Inspired by recent beneficiation processes for the production of titanium from South Africa's vast mineral resources, this study identified the opportunity to create sustainable value from the inevitable influx of scrap, once these beneficiation strategies have been implemented. The objectives were to research all methods capable of recycling titanium, map their process chains, and model them financially. Furthermore, a feasibility framework was to be created, which serves the purpose of showing when each recycling method becomes financially feasible. Finally, a business case was to be created after choosing the best recycling alternative in South Africa at the time of the study. A background study was done at Hansens Engineering in Port Elizabeth, to gain insight into a state-of-the-art waste-to-resource process through their in-house aluminium recycling operations. Eight methods of recycling titanium are identified in the literature review, namely washing and briquetting swarf, precision casting, thermal degreasing, ferrotitanium production, vacuum-arc remelting (VAR), electron beam cold hearth melting (EB CHM), plasma arc cold hearth melting (PA CHM) and mill product production. Each process is modelled financially, by use of a factorial method, which utilises equipment, operating labour, waste treatment, utilities and raw material costs as input variables to estimate total fixed capital investment and total manufacturing costs. A ten-year NPV analysis on each process is done, which is used to conduct the feasibility study, which consists of break-even analysis, scenario analysis, and the creation of the feasibility framework. The break-even analysis determines the yearly volume of scrap required to make each recycling method financially feasible. By use of this, the feasibility framework is created. The break-even volumes are contextualised by use of benchmark components. This is used to represent the break-even points of each recycling method in terms of an amount of components, as opposed to a volume of titanium scrap. The financial feasibility models are also used to perform scenario analysis using pessimistic and optimistic hypothetical swarf availabilities, based on South African titanium trade statistics. Based on the collective feasibility study results, it is found that only two of the eight recycling processes are financially feasible at present, namely washing and briquetting swarf, and precision casting. The best option for recycling titanium at present is identified as precision casting, which shows a positive

NPV of R650.55 million and R81.96 million in the optimistic and pessimistic hypothetical scrap availabilities, respectively. Uncertainty analysis is performed on this process through the use of Monte-Carlo simulation. Input variables are varied over probable ranges, or by fitting distributions on historical data, to predict the probability of having a positive NPV after the analysis period. The results showed that when recycling titanium through precision casting, one can be almost 99% certain of having a positive NPV after ten years, when implementing either a 150% fixed profit margin or a selling price of R1000 per casting. By this, a business case for titanium recycling in South Africa is created.

# Uittreksel

## ’n Haalbaarheidstudie vir Titaan Herwinning in Suid-Afrika

*(“A Feasibility Study for Titanium Recycling in South Africa”)*

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In hierdie studie word die moontlikheid van titaan herwinning in Suid-Afrika ondersoek. Genïspireer deur onlangse waardetoevoegingsprosesse vir die produksie van titaan uit minerale hulpbronne in Suid-Afrika, identifiseer hierdie studie die geleentheid om volhoubare waarde te skep uit die onvermydelike instroming van skroot, wanneer hierdie waardetoevoegings strategieë in werking gestel word. Die doelstellings was om al die metodes wat beskikbaar is om titaan te herwin te identifiseer, hul proses kettings op te teken, en hul finansieel te modelleer. Verder is ’n haalbaarheidsraamwerk geskep, met die doel om uit te beeld wanneer elke herwinningsproses finansieel haalbaar raak. ’n Besigheidsgeleentheid is geskep vir die beste herwinningsalternatief in Suid-Afrika in die huidige klimaat van die Suid-Afrikaanse titaanindustrie. ’n Agtergrondstudie is gedoen by Hansens Engineering in Port Elizabeth, om insig te kry in ’n moderne afval-tot-hulpbron proses, waar hulle binnenshuis aluminium herwin. Agt metodes van titaan herwinning is geïdentifiseer in die literatuurstudie, naamlik was-en-“briquette”, “precision casting”, “thermal degreasing”, ferrotitaan produksie, “vacuum-arc remelting” (VAR), “electron beam cold hearth melting” (EB CHM), “plasma arc cold hearth melting” (PA CHM) en “mill product” produksie. Elke proses is finansieel gemodelleer, deur die gebruik van ’n faktoriale metode, wat insette gebruik in die vorm van toerusting-, arbeids-, afval behandeling-, water- en eletrisiteits- en grondstofkoste om die totale vastekapitaalbelegging en totale produksiekoste te beraam. ’n Tien jaar NHW-analise op elke proses is gedoen, wat gebruik word om die haalbaarheidstudie uit te voer. Die haalbaarheidstudie bestaan uit ’n gelykbreek analise, scenario analise en die ontwikkeling van die haalbaarheidsraamwerk. The gelykbreek analise bepaal die volume skroot benodig om elke herwinningsproses finansieel haalbaar te maak. Dié analise word dan ook gebruik om die haalbaarheidsraamwerk op te stel. The gelykbreek punte vir elke proses word gekontekstualiseer deur middel van maatstafkomponente. Dit beeld die gelykbreekpunte van elke proses uit as ’n aantal komponente, in plaas van ’n volume skroot. Die finansiële haalbaarheidsmodelle word ook gebruik om ’n scenario analise uit te voer met behulp van pessimistiese en optimistiese hipotetiese skroot beskikbaarhede, gebaseer op Suid-Afrikaanse titanium skroot handelstatistieke. Op grond van die gesamentlike lewensvatbaarheidstudie resultate, is daar gevind dat slegs twee van die agt herwinningsprosesse huidiglik finansieel haalbaar is, naamlike die was-en-“briquette” proses en “precision casting”. Die beste opsie vir herwinning van titaan op die oomblik is geïdentifiseer as “precision casting”, wat ’n positiewe NHW van R650.55-miljoen en R81.96-miljoen vir optimistiese en pessimistiese hipotetiese skroot beskikbaarhede toon. Onsekerheidsontleding is op hierdie proses toegepas deur die gebruik van ’n Monte-Carlo simulasie. Insetveranderlikes word gewissel oor hul waarskynlike reekse of deur distribusies op hulle historiese data te pas. Die waarkynlikheid van ’n positiewe NHW na die tien-jaar tydperk kan dan bepaal word. Die resultate het getoon dat daar byna ’n 99% waarskynlikheid is van ’n positiewe NHW na tien jaar, wanneer die simulasie ’n winsmarge van 150% of ’n vaste verkoopprys van R1000 per eindproduk het. Deur middel van dié simulasie, is ’n besigheidsgeleentheid vir titaan herwinning in Suid-Afrika geskep.

# Acknowledgements

I would like to express my sincere gratitude to the following people and organisations:

- Dr GA Oosthuizen for being the primary supervisor of this thesis and identifying the initial problem.
- Mr WG Bam for acting as co-supervisor in this project.
- Joalet Steenkamp of Mintek, for her ongoing assistance in this project and for introducing me to many of the people involved with this project.
- Mike Saxer of the STC-LAM, for providing valuable insights into the problems encountered with titanium scrap at the lab and general insights into the South African titanium industry, machining of titanium and the benchmark components used for project validation.
- Philip Hugo of the STC-LAM, for additional insights into titanium scrap and advice with regards to investment casting and melting of titanium in general.
- Scott Jackson of American Titanium Works, for providing valuable insights into the American titanium recycling industry and sharing his personal experiences and expertise with regards to titanium recycling. Additionally, for providing both financial and operational data of his recycling operations, as well as general titanium scrap and product prices.
- Willem van Niekerk of Exarro, for introducing me to the American titanium industry and insights into the South African titanium mineral industry.
- Pieter Conradie for providing me with titanium benchmark components used in his study.
- Erik Hagedorn-Hansen of Hansens Engineering, for making time in his busy schedule to take me through his facility for my case study as well as providing data and

insights on the aluminium recycling industry and data for my case study.

- Simon Halse of Granroth, for cost and throughput estimations of scrap processing equipment, as well as labour requirements.
- Markus Nortemann of Hansens Engineering, for scrap treatment and minimum quantity lubrication cost data.
- Jacques Marais of CSI Africa, for flood lubrication treatment and disposal cost data.
- Ulrich Betz of ALD Vacuum Technologies, for quotations for precision vacuum casting equipment for titanium scrap.
- Daniel Zeelie of Saveway Furnace Monitoring Africa (Pty) Ltd, for cost estimations for induction furnaces for the production of ferrotitanium.
- Jennifer Ziegler and Tamara Shaffner of Linn High Therm GmbH, for detailed quotations on small scale precision vacuum casting equipment.
- Konrad von Leipzig of Stellenbosch University for providing licenses for the @Risk software used for financial modelling of the problem.
- Ruan Muller of Baker Tilly Greenwoods for advice on financial analysis.
- Tamsyn Lunt of GetSmarter for text editing and grammatical review.
- Pierre Rossouw of the CSIR for advice on titanium precision casting furnaces.

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# Nomenclature

### Constants

| | |
|---|---|
| n = | 0.6 |

### Variables

| | |
|---|---|
| A | Equipment Cost Attribute |
| C | Cost |
| $C_i$ | Inflated Cost |
| $C_{OL}$ | Cost of Operating Labour |
| $C_p$ | Cost in a Base Year |
| $C_{p,i}$ | Purchased Cost for Major Equipment Units |
| $C_{RM}$ | Cost of Raw Materials |
| $C_{TM}$ | Capital Cost (Total Module) of the plant |
| $C_{UT}$ | Cost of Utilities |
| $C_{WT}$ | Cost of Waste Treatment |
| COM | Cost of Manufacture |
| D | Depreciation Value |
| DMC | Direct Manufacturing Costs |
| DPBP | Discounted Payback Period |
| F | Future Value |
| $f_n$ | Inflation Rate in the $n^{th}$ Year |
| $F_{Lang}$ | The Lang Factor |
| FCI | Fixed Capital Investment |
| FMC | Fixed Manufacturing Costs |
| GE | General Expenses |
| I | Cost Index |
| i | Interest Rate |
| $i_{eff}$ | Effective Annual Interest Rate |
| $i_{nom}$ | Nominal Interest Rate |
| $k_c$ | Cutting Force |
| m | Number of Compounding Periods per Year |
| NPV | Net Present Value |
| POP + I | Payback Period Plus Interest |
| PVR | Present Value Ratio |

| | |
|---|---|
| R | Revenue from Sales |
| S | Salvage Value |
| t | Tax Rate |

**Subscripts**

| | |
|---|---|
| a | Equipment with Required Attribute |
| b | Equipment with Base Attribute |

**Abbreviations**

| | |
|---|---|
| AIC | Akaike Information Criterion |
| Al | Aluminium |
| AMI | Advanced Materials Initiative |
| BAT | Best Available Techniques |
| CAD | Computer Aided Design |
| CEPCI | Chemical Plant Cost Index |
| CHM | Cold Hearth Melting |
| CP | Commercially Pure |
| CR | Old Scrap Collection Rate |
| CSIR | Council for Scientific and Industrial Research |
| CUT | Central University of Technology |
| DC | Direct Current |
| DDB | Double-Declining-Balance-Depreciation |
| DOSS | Deoxidised in the Solid State |
| DST | Department of Science and Technology |
| DTI | Department of Trade and Industry |
| EB | Electron Beam |
| EOL | End-of-life |
| ESR | Electroslag Remelting |
| EU | European Union |
| GST | Goods and Services Tax |
| HDH | Hydride-Dehydride |
| HDI | High Density Inclusion |
| HID | High Interstitial Defect |
| ISM | Induction Skull Melting |
| LMDN | Light Metals Development Network |
| M-C | Monte-Carlo |
| MQL | Minimum Quantity Lubrication |
| NC | Non-consumable |
| NMMU | Nelson Mandela Metropolitan University |
| OSR | Old Scrap Ratio |
| PA | Plasma Arc |

| | |
|---|---|
| PSD | Particle Size Distribution |
| RBM | Richards Bay Minerals |
| RC | Recycled Content |
| RIR | Recycling Input Rate |
| RMI | Rare Metals Industries |
| RR | Recycling Rate |
| SARS | South African Revenue Service |
| SL | Straight-Line |
| SOYD | Sum-of-the-Years-Digits-Depreciation |
| STC-LAM | Stellenbosch Technology Centre - Laboratory of Advanced Manufacturing |
| SU | Stellenbosch University |
| TBI | Titanium Beneficiation Initiative |
| Ti | Titanium |
| TiCoC | Titanium Centre of Competence |
| UCT | University of Cape Town |
| UNEP | United Nation Environmental Program |
| V | Vanadium |
| VADER | Vacuum-Arc Double Electron Remelting |
| VAR | Vacuum-Arc Remelting |
| VIM | Vacuum Induction Melting |

**Units of Measure**

| | |
|---|---|
| HB | Brinell Hardness |
| kg | Kilogram |
| kt | Kilo tonnes |
| ktpy | Kilo tonnes per year |
| kWh | Kilowatt Hours |
| m | Metres |
| Mt | Metric Tonnes |
| N | Newton |
| Pa | Pascal |
| s | Seconds |

# Chapter 1

# Introduction

In this chapter the research problem and background are explained. Key ideas around the global and South African titanium situation are discussed, with emphasis on the aerospace industry, titanium minerals and beneficiation thereof, scrap creation, and recycling. This gives a brief background on the research problem. Also discussed are the aims and objectives of the project, which helps to clarify why the research is being conducted. In conclusion, the limiting factors and scope of the research are discussed.

## 1.1 Background and Motivation

Traditionally associated with the aerospace industry, titanium's unique properties makes it a suitable alternative in any application where light alloys are generally used. Its high strength-to-weight ratio makes it ideal for use in the construction of aircraft, where around 50% of the metal is used. More recently, its superior corrosion resistance and biocompatibility has made it an attractive option for the chemical industry and the medical profession, where it is used in implants. Titanium metal's high price is the primary reason for it not being adopted more frequently in other markets.

Titanium is, rather unexpectedly, very common and widespread throughout the planet and is the earth's fourth most abundant structural resource, making up around 0.6% of the crust (McQuillan and McQuillan, 1956). According to Polmear (2006), around 93% of titanium minerals extracted are consumed in the form of titanium oxide. This substance is used as a white pigment in paint, papermaking, printing ink, ceramics and plastics. Currently, as little as 3% of titanium mineral production is converted to titanium metal (Roskill Information Services Ltd, 2013).

It is thus not the metal's scarcity which drives up its price, but its tedious and challenging production process. Processing titanium to its metal form is expensive and time consuming. The Kroll process, used to produce titanium sponge, is partly to blame for this. Titanium has a high reactivity with other elements, especially oxygen, nitrogen, hydrogen and carbon (Polmear, 2006). This property means that melting of titanium cannot be carried out in air or normal crucibles and needs to be melted in high temperature, oxygen-free environments. Further, downstream processing, such as the production of titanium mill products, also incurs massive costs, making up about 50% total production costs (Roskill Information Services Ltd, 2013).

South Africa is the second largest producer of titanium minerals in the world, but none of the minerals extracted are converted to titanium metal locally on a commercial scale. The majority of these minerals are exported, where a small fraction is processed to metal in first-world countries and local titanium component manufacturers are forced to buy back these metal products at high prices. Beneficiation strategies have been put in place by government to create greater value from these natural resources.

A novel process of producing titanium metal powder, known as the CSIR-Ti process, has been developed locally. Pilot scale tests on this process have been conducted, and the current plant is capable of producing 2kg of titanium powder per hour. As support for titanium benficiation grew, the Titanium Centre of Competence (TiCoC) was established in 2009 to develop local knowledge around the technology required for a local titanium industry. This thesis forms part of the project: "Resource Efficient Process Chains for Titanium Components in Aerospace, Automotive, and Medical Applications ", which is a project of the TiCoC network. Titanium research done at Stellenbosch University is largely focussed on reducing waste and improving machining time of titanium components for industry. Primary targets for the project are set to reduce material usage by 50% and machine time by 20%. This is done by implementing pre-forms and near-net shape manufacturing technologies. Industrial partners for the project are Aerosud, Daliff Precision Engineering and Southern Implants.

Local companies such as Denel, Daliff and Aerosud produce titanium parts for world-leaders in the aerospace industry using imported titanium mill products. Aerosud has demonstrated its competency in producing aluminium aerospace structural components for Airbus. Production has mainly focussed on the Airbus A400M. Daliff produces high value added machined components for the aerospace, defence, nuclear and medical industries. Southern Implants have a 1% global market share of the titanium implants industry. These companies produce a fair amount of titanium scrap in the form of machine chips, also known as turnings or swarf. An example can be seen in Figure 1.1, gathered from the machining experiments of thin walled titanium components at the Stellenbosch Technology Centre - Laboratory for Advanced Manufacturing (STC-LAM). Titanium parts produced for the aeropace industry have a high "buy-to-fly" ratio of about 5:1, meaning that around 80% of raw material is scrapped. This provides a good source of high quality titanium metal scrap, with traceable origins.

Scrap is sold to titanium scrap dealers locally at general non-ferrous or non-magnetic scrap prices, as local scrap dealers do not have sufficient knowledge of the metal. This presents a dilemma for titanium fabricators, as a very high price is paid to import titanium mill products, of which over 80% is reduced to waste and which is sold again at a very low price. Titanium part fabricators have the additional option of exporting this machine swarf, and thereby getting a fair price, but this requires large quantities of scrap and possibly long-term contracts. Although the price is higher when selling to international buyers, local titanium scrap will often be sold as the lower quality, ferrograde scrap, because of the high controls on the quality of scrap used in titanium recycling. There may be an option to recycle this scrap locally, thereby removing the need for fabricators to export their scrap or settle for a lower scrap price because of scrap dealers' ignorance. Local small scale recycling might thus already be financially feasible in the current state of South Africa's titanium industry. This research seeks to find the best option for recycling of titanium machine scrap from a financial perspective.

**Figure 1.1:** Titanium Swarf

It is important that the value created from the beneficiation initiatives be sustainable and stays in the country. Successful beneficiation strategies will boost all downstream operations of the titanium industry. This includes an inevitable influx of titanium scrap. This research thus seeks to explore all possibilities of recycling, even options which are currently infeasible. By doing this, this research remains relevant and useful after the successful implementation of beneficiation strategies and can be used in the future to make informed decisions for recycling strategies.

## 1.2 Project Aim and Objectives

This research aims to investigate titanium recycling, and thereby identify all recycling methods used in practice. The study seeks to determine the financial feasibility of these methods. Thereby, not only assisting in deciding which recycling option is best at present, but also in determining which recycling option is best in future scenarios. The main goal is to assist with creating greater value from locally produced scrap and identify the best method to accomplish this. In order to accomplish these aims, three main objectives are identified. The objectives of this study are as follows:

- Research, map and model all methods of recycling titanium scrap.
- Create a framework and cost models to assess the feasibility of titanium recycling alternatives in South Africa.
- Create a business case for titanium recycling through a simulation model.

## 1.3 Limitations and Scope

This study concentrates primarily on the most widely used titanium alloy, Ti-6Al-4V, as it is used by South African aerospace manufacturers. The scope of the study entails the process from scrap creation, where titanium parts are machined, to possible end-use products. Intermediate steps of scrap processing, primary melting and conversion to mill products are addressed. Melting via vacuum-arc, electron beam, plasma arc and cold wall induction are considered. Production to ferrotitanium via vacuum induction melting is also investigated.

Only scrap sourced from manufacturing processes (so called 'new scrap'), and not salvaged scrap from end-of-life products ('old scrap'), is addressed as these sources are not common in South Africa. Emphasis is put on recycling of machine turnings, but solid scrap is also looked at briefly. It is assumed that the titanium swarf has been kept separate from other metals in machining, and is not gathered in batches mixed with these metals. Physical melting experiments are not done in this study.

The model built includes following financial parameters. For initial capital investment costs: equipment, erection of items, structural and buildings, civils, piping and ducting, electrical and instruments. Additional measures which account for GST, site preparation, construction management and contingency are incorporated. Manufacturing costs include the following parameters: direct manufacturing costs, fixed manufacturing costs and general expenses. Direct manufacturing costs include raw materials, waste treatment, utilities, operating labour, direct labour, direct supervisory and clerical labour, maintenance and repairs, operating supplies, laboratory charges, and patents and royalties. Fixed manufacturing costs consist of depreciation, taxes and insurance, and plant overhead costs. General expenses are comprised of administration, distribution and selling, and research and development.

Any additional direct cost factors are not accounted for in this model. The financial feasibility model incorporates Lang Factors, which according to Turton *et al.* (2008) can be expected to give results which are 72% above budget or 48% below budget in the worst and best-case scenarios.

# Chapter 2

# Literature Study: Titanium Metal - Properties, Applications and Production

In this chapter a literature review is done on titanium as a metal to give greater insight into the properties, applications and production process of the metal. The metal's material properties are given and through this it is explained why it is suitable to specific applications. Special attention is given to titanium applications in aerospace, industrial, and biomedical industries.

A brief overview is given of the primary production process, explaining minerals processing, titanium sponge production, melting processes and final mill product production; the form in which the metal is imported to South Africa. Furthermore, a market overview is given, which gives some trade statistics of titanium. This is followed by current and historical beneficiation strategies and finally, an overview of the current and historical titanium metal prices.

## 2.1 Properties and Applications

The engineering group Sandvik explains in Sandvik Coromant (2004) that titanium alloys fall into three classes, namely alpha ($\alpha$) alloys, beta ($\beta$) alloys and mixed ($\alpha$+$\beta$) alloys. Alpha alloys contain alloying elements such as aluminium, oxygen or nitrogen, which stabilise the alpha phase, while molybdenum, iron, vanadium, chromium and/or manganese are used to stabilise the beta phase. The titanium alloy Ti-6Al-4V, which this research focuses on, is the most widely used titanium alloy in the world, both for aerospace applications and general use. Ti-6Al-4V falls into the mixed category and has a tensile strength of 900 N.mm$^{-2}$, a hardness of 310 to 350 HB and a specific cutting force of 1400 k$_c$/MPa. Seong *et al.* (2009) states that titanium is as strong as steel, but 45% lighter. Compared to aluminium it is 60% heavier, but twice as strong. A comparison of the properties of commercially pure (CP) and the Ti-6Al-4V alloy to other materials is given in Table 2.1.

Titanium metal can be consumed in any application where the benefit gained from its three most desirable properties (strength, weight and corrosion resisitance) outweighs the high cost of the metal. Figure 2.1 shows the metal's most desirable material charac-

| Material | Density [kg/cm$^3$] | Young's Modulus [MPa] | Tensile Strength [MPa] | High Temperature Oxidation | Corrosion Resistance |
|---|---|---|---|---|---|
| Steel | 7.85 | 205 | 400-800 | High | No |
| Stainless Steel | 7.95 | 200 | 600 | High | Moderate |
| CP Titanium | 4.51 | 106 | 450 | Moderate | High |
| Ti-6Al-4V | 4.43 | 114 | 900 | High | High |
| Al Alloy | 2.70 | 70 | 250 | No | No |
| Mg Alloy | 1.70 | 45 | 200 | No | No |
| Plastic (SMC) | 1.90 | 10 | 300 | No | Moderate |

**Table 2.1:** Material Property Comparison. Adapted from Yamashita *et al.* (2002)

teristics, combined with some of its most common applications. The primary consumers of titanium metal are the industrial sector, consuming about 52%, and the aerospace industry, making up about 36% (Roskill Information Services Ltd, 2013). The remainder is made up of the automotive industry, military hardware, sports and recreation, the biomedical industry and some other applications. Titanium metal's strength-to-weight ratio and heat resistance makes it a very important metal in commercial aerospace and an essential material to many military aeroplanes. The material's high corrosion resistance is the most attractive property for other applications.

China is the largest consumer of titanium (32%), followed by the United States (25%) and then the EU (18%) (Roskill Information Services Ltd, 2013). The application of titanium differs depending on the area of consumption. U.S. Geological Survey (2015*a*) states that 75% of titanium metal was used in the aerospace industry in the United States, while the rest was used in armour, chemical processing, marine hardware applications, medical implants, power generation, sporting goods, and other application areas. Use of titanium metal in China, Japan and other Asian markets is largely in industrial applications, particularly chemical plants (Roskill Information Services Ltd, 2013).

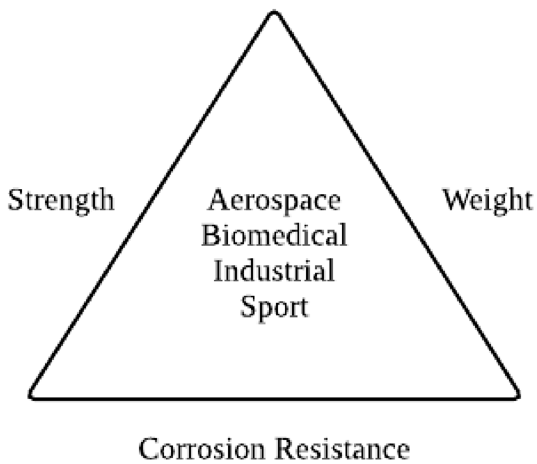


**Figure 2.1:** Important Characteristics for Titanium Applications. Adapted from Faller and Froes (2001)

As previously stated, titanium is quite abundant in nature, but the cost of processing it to its metal form is very high compared to other structural metals. This is the major limiting factor in the widespread use of titanium in more applications. Table 2.2 compares the production cost of steel, aluminium and titanium from a study by Hurless and Froes (2002). Aluminium is taken as the normalised cost, and it can be seen how expensive titanium production is relative to aluminium, with all stages of production much more expensive than that of aluminium and steel. In its sheet form, titanium production is 18 times more expensive than aluminium and 45 times more expensive than the steel equivalent. Explained below are industries in which titanium material properties are important enough to justify this high material cost.

| Production Stage | Steel | Aluminium | Titanium |
|---|---|---|---|
| Metal Refining | 0.4 | 1.0 | 5.0 |
| Ingot Forming | 0.6 | 1.0 | 10.7 |
| Sheet Forming | 0.4 | 1.0 | 18.0 |

**Table 2.2:** Cost Comparison of the Stages of Metal Production (Hurless and Froes, 2002)

### 2.1.1 Aerospace

In the United States of America, the majority of titanium metal is used in the aerospace industry. According to Moiseyev (2006), 31% is used in commercial aircraft engines, 20% in military aircraft engines, 15% in commercial airframes, 10% in military airframes, 7% in space rocketry, and 1% in helicopters and armaments, totalling about 84%.

Having the highest strength-weight ratio of any modern structural material, it is understandable why its use in the industry is so widespread. By substituting titanium alloys for steels and aluminium alloys, the weight of the aircraft is reduced and gives aircraft a higher weight efficiency. In supersonic aircraft, titanium is essential, as steel is too heavy and aluminium is not able to resist the high heats of supersonic flight.

According to Moiseyev (2006), the use of titanium in commercial airframes will increase to 15% of the airframe weight and in supersonic aircraft, it is expected to increase to between 40% and 95% of the airframe weight. He states that airframe parts such as the skin, wing frame, components of fasteners, chassis and wing mechanization, pylons, hydraulic cylinders and various aggregates can be created from titanium alloys. In current commercial aircraft, titanium makes up about 7% of of the airframe weight and 36% of the engine weight (Peters *et al.*, 2003).

South African production of titanium metal products is rather small. South African based companies such as Denel Aerostructures and Aerosud produce titanium aerospace parts for major international aviation companies, Airbus and Boeing. Denel aerostructures is currently producing parts for the military Airbus A400M, which contains about 9 tonnes of titanium metal per aircraft (Roskill Information Services Ltd, 2013; Denel Aerostructures, 2015).

### 2.1.2 Industrial

Titanium is used within the chemical and petrochemical, power, oil and gas, water supply, automotove, marine, and construction industries. Within the chemical and petrochemical, power generation, desalination and other industries, the largest application of titanium is plate heat exchangers (Roskill Information Services Ltd, 2013). The use for titanium for industrial components is much more prominent in Asia, with China accounting for about half of global titanium in industrial uses (Roskill Information Services Ltd, 2013). According to Roskill Information Services Ltd (2013), titanium's corrosion resistance is the property most desirable in these industrial applications, with its low density, high strength, high temperature tolerance and high heat transfer efficiency also sought after in some industries.

### 2.1.3 Biomedical

Titanium alloys are used in biomedical devices because of its relatively low modulus of elasticity, good fatigue strength, formability, machinability, corrosion resistance, and superior biocompatibility (Cui *et al.*, 2011; Niinomi, 1998). Artificial materials are commonly used for replacement of hard tissue in the human body, which are damaged due to accidents, aging or other causes. Titanium is used specifically as artificial bones and joints, and as dental implants (Cui *et al.*, 2011).

Titanium hip joints are some of the most common applications of titanium in the biomedical field. They consist of an articulating bearing and stem. Titanium knee joint replacements are also commonly seen, which consist of a femoral component, tibial component and patella. The titanium alloy Ti-6Al-4V and commercially pure titanium are most widely used as implants, despite being developed as structural materials (Cui *et al.*, 2011; Niinomi, 1998). South African-based company, TiTaMED, produces biomedical titanium products, such as implantable medical devices. Southern Implants, also based in South Africa, produces titanium dental implants.

### 2.1.4 Other Industries

Titanium is consumed in smaller quantities in recreational and sporting uses. Golf is the largest contributor to titanium use in other applications. Bicycle frames are another sporting application which makes a noticeable contribution to titanium use. The use of titanium in sporting and family vehicles is also discussed in this section.

The use of titanium to produce golf woods has become very common in recent times. Hollow titanium driver heads allow a larger head in volume, with a lower weight, resulting in a club that supposedly gives greater distance, a straighter shot, and a higher moment of inertia (Shira and Froes, 1997). Golf clubs are by far the most popular consumer item produced from titanium, accounting for almost 25% of titanium mill product shipments in the United States in 1996 (Roskill Information Services Ltd, 2013; Shira and Froes, 1997).

Bicycle frames produced from titanium is a small market, estimated at about 200 tonnes per annum worldwide. The value added to frames is higher than any industrial or aerospace application, with frames weighing a few kilograms selling for up to $ 3500

(Roskill Information Services Ltd, 2013). In 1997 the entire weight of the world production of titanium bicycle frames was less than that contained in three Boeing 747 aircrafts (about 130 tonnes) (Vandermark, 1997).

The use of titanium in the automotive industry is large restricted to speciality vehicles, where the high cost of titanium justifies the marginal performance improvements. In racing applications, titanium's reduced weight is the preferred technology in engine valves and connecting rods, as well as mufflers and exhaust header pipes in racing motorcycles (Faller and Froes, 2001).

In family motors, titanium can be beneficial by improving fuel economy, reducing engine noise and vibration, and improve durability (Faller and Froes, 2001). Titanium has a moderate to high chance of replacing turbocharger compressor rotors, engine valves, leaf springs, turbocharger turbine rotors, valve trains and piston caps, pins, and connecting rods in heavy vehicles (Kraft, 2002). Components in family cars which could be replaced by titanium, include engine valves, connecting rods and valve springs and their containers, sealing washers, brake pistons, wheel bolts, wheel hubs, wheels, suspension springs, exhausts, crash elements, armour, and stabilisers (Faller and Froes, 2001; Yamashita *et al.*, 2002; Schauerte, 2003).

While there is potential to replace these components with titanium, conventional materials will not be replaced until lower cost titanium parts can be produced. Potential drivers to accomplish this may be by the advancement of research in titanium aluminides, low-cost powders, metal injection moulding, metal mould castings, melt processes using hydride powders, and the recycling of titanium machine chips (Sachdev *et al.*, 2012).

## 2.2 Production Process

The most widely used production process is explained in this section. It is popular for titanium scrap to be recycled through the primary production route. As previously mentioned, titanium metal is expensive to produce and follows a complex process.

Titanium ore can be processed to titanium metal parts through a few processes, which can be seen in Figure 2.2. The figure shows both establised and emerging technologies for the production of titanium parts. Of the technologies cited in the image, Kroll, electron beam melting, plasma arc melting, vacuum arc remelting, hydride-dehydride, machining, forging, and casting are addressed in this study. These are the technologies which utilise or produce scrap, or are used to produce a final part from the recycled scrap.

The most common method of titanium metal production is by a combination of the Kroll process, vacuum arc remelting (VAR) and primary fabrication processes. The Kroll process produces titanium sponge, which is an intermediate product of commercially pure (CP) titanium, so-called because of its porous, sponge-like appearance (Seong *et al.*, 2009). VAR is used to produce titanium ingots by melting the sponge with alloying components in a vacuum. These ingots are then processed to mill products, such as plate, sheet, billet, and bar. This is done through primary fabrication processes, such as rolling and forging. Final parts are then produced by secondary fabrication processes such as forging, extrusion, hot and cold forming, machining, and casting (Seong *et al.*, 2009; Roskill

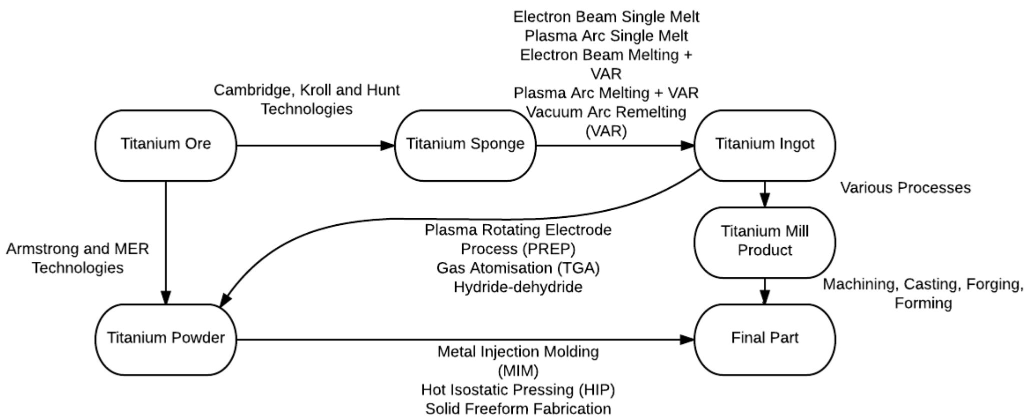


**Figure 2.2:** Technologies for Titanium Metal Production (Seong *et al.*, 2009; Cui *et al.*, 2011)

Information Services Ltd, 2013).

This section will briefly describe these processes, starting from heavy minerals to mill product production, and review the major players in the titanium market.

### 2.2.1 Heavy Minerals

Titanium is sourced from nature in the form of ilmenite ($FeO.TiO_2$) and rutile ($TiO_2$). Ilmenite accounts for approximately 90% of the world's demand for titanium minerals. China (200Mt), Australia (118Mt), India (92Mt) and South Africa (71Mt) have the largest reserves of titanium, together containing about 70% of world reserves (Maphango *et al.*, 2013).

In 2014, South Africa produced 1100 kt ilmenite and 65 kt of rutile, ranking it tied first with Australia for ilmenite production and third, behind Australia and Sierra Leone, in rutile production (U.S. Geological Survey, 2015*a*). Despite this, the country does not produce any titanium metal on an industrial scale. The largest producers of titanium minerals in South Africa are Richards Bay Minerals (RBM), Namakwa Sands and KZN Sands (Maphango *et al.*, 2013).

The current state of the South African heavy minerals industry is explained in detail by Motsie *et al.* (2010). According to the source, Richards Bay Minerals (RBM) mines heavy minerals at the Tisand (Pty) Ltd mine. Heavy minerals are produced by floating dredge and gravity separation of dune sands. Further processing is done by magnetic and electrostatic techniques. They have a processing plant, which processes the Tisand to titania slag and high purity pig iron. The same source states that Exarro Ltd owns Hillendale Mine in Empangeni and Namakwa Sands in Vrendenburg. Both these mines have facilities for mineral separation and titanium slag smelters to produce ilmenite, zircon, and rutile and to process this to titania slag.

### 2.2.2 Sponge

Titanium sponge is produced by the Kroll process. The process is explained as follows by Roskill Information Services Ltd (2013), Leyens and Peters (2003) and Seong *et al.*

(2009). Feedstock with a $TiO_2$ content of more that 85% is used and mixed with high purity coke and chlorine. The first step is to chlorinate and then distil it, to remove metallic impurities. Titanium tetrachloride is produced by heating the mixture in a fluidised bed reactor to between 850 ℃ and 950 ℃. By reduction with magnesium, the mixture is reduced to titanium sponge. Remaining magnesium and magnesium chloride is then removed by vacuum distillation. Finally, the sponge is sheared and crushed. When titanium is reduced by sodium, instead of magnesium, the process is known as the Hunter process.

| Country | Sponge Capacity [kt] |
|---|---|
| United States | 24 |
| China | 114 |
| Japan | 57 |
| Kazakhstan | 27 |
| Russia | 46.5 |
| Ukraine | 10 |
| Total | 279 |

**Table 2.3:** Sponge Capacity by Country in 2014 (U.S. Geological Survey, 2015*a*)

In 2014, six countries produced titanium sponge worldwide (U.S. Geological Survey, 2015*a*). The sponge capacity of these countries can be seen in Table 2.3. Twenty-three companies produced this titanium sponge. Large players in sponge production include VSMPO-Avisma, Timet, ATI, Honeywell Electronic Materials, Osaka Titanium Technologies, Toho Titanium, UKTMP, ZTMC, Zunyi Titanium and Baoji Titanium (Roskill Information Services Ltd, 2013).

### 2.2.3 Melted Products

To produce titanium ingots, titanium scrap is mixed together with titanium sponge and melted down. Ingots are generally produced by one of three technologies, vacuum-arc remelting (VAR), cold-hearth melting (CHM) or induction skull melting (ISM). According to Roskill Information Services Ltd (2013), in 2013, fourty-two plants produced the world supply of 380 ktpy of titanium melted products.

These plants are located in eight countries around the world and belong to thirty-eight different companies. Table 2.4 shows a list of all major companies producing titanium melted products. Of particular interest are countries which have no sponge production capacity, but produce titanium melted products. This is an encouraging sign for a country such as South Africa, which may be able to build a similar industry by using local scrap and imported sponge. The UK, Germany, France and Italy are all producing melted products, with imported sponge and/or local or imported scrap.

The most popular method of creating titanium ingots is by vacuum-arc remelting furnace. By this method, cylindrical titanium ingots are produced. VAR requires between 4.4 kWh and 5.5 kWh to produce 1 kg of titanium metal (Roskill Information Services Ltd, 2013). VAR is used to produce high quality ingots, repeating the melt twice or even

| Company | Location | Capacity [ktpy] |
|---|---|---|
| Baoji Lixing Titanium | Baoji, China | 2.0 |
| Baoji Titanium Industry | Baoji, China | 30.0 |
| Baojin First Titanium | Baoji, China | 1.0 |
| Baosteel | Shanghai, China | 10.0 |
| Beijing Hongda Titanium | Beijing, China | 2.0 |
| BIAM | Beijing, China | 2.0 |
| Beijing Zhongbei Titanium | Beijing, China | 3.0 |
| Cixi Wuhuan Titanium Holding | Cixi, China | 2.5 |
| Donggang Dongfang Hi-Tech Company | Dandong City, China | 1.2 |
| Hebei Delin Titanium Industry | Hebei, China | 2.0 |
| Hunan Xiangtou Goldsky New Materials | Hunan, China | 5.0 |
| Luoyang Ship Materials Research Institute | Luoyang, China | 1.5 |
| Nanjiang Baotai Special Materials | Nanjing, China | 0.9 |
| Pangang Group Sichuan Chancheng | Panzhihua City, China | 4.0 |
| Shenyang Beifang Titanium | Shenyang, China | 0.7 |
| Western Titanium Technologies | Xian, China | 5.0 |
| Zhangjiagang Haian Titanium | Suzhou, China | 0.6 |
| Zunyi Titanium Stock | Zunyi, China | 2.0 |
| Timet Savoie | Ugine, France | 3.2 |
| Outokumpu VDM | Essen, Germany | 11.0 |
| Tifast | San Liberato di Narni, Italy | 2.0 |
| Daido Steel | Chita, Japan | 1.5 |
| Kobe Steel | Kobe Prefecture, Japan | 13.0 |
| Osaka Titanium technologies | Amagasaki, Japan | 10.0 |
| Toho Titanium | Chigasaki and Hitachi, Japan | 28.0 |
| UKTMP | Ust Kamenogorsk, Kazakhstan | 9.0 |
| Stupino Titanium Company | Stupino City, Russia | 2.0 |
| Vils JSC (Institute of Light Alloys) | Moscow, Russia | 1.0 |
| VSMPO/Avisma | Verkhnaye Salda, Russia | 50.0 |
| BM Strategy | Kiev, Ukraine | 1.0 |
| Industrial Concern Fiko Group | Kiev, Ukraine | 3.0 |
| MK Antares | Kiev, Ukraine | 5.0 |
| Timet UK | Witton, UK | 10.7 |
| Alcoa Howmet | Whitehall, MI, USA | 3.2 |
| Allegheny Technologies | Albany, OR, USA | 10.9 |
| Allegheny Technologies | Monro, NC, USA | 23.2 |
| Allegheny Technologies | Richland, WA, USA | 10.0 |
| Alloy Works | Greensboro, NC, USA | 1.8 |
| Perryman Co | Houston, PA, USA | 1.8 |
| RTI International Metals | Niles, OH, USA | 22.2 |
| Timet | Henderson, NV, USA | 22.2 |
| Timet | Morgantown, PA, USA | 40.7 |
| Timet | Vallejo, CA, USA | 1.6 |

**Table 2.4:** List of Primary Titanium Ingot and Slab Producers (Roskill Information Services Ltd, 2013)

three times to increase homogeneity and reduce the gas content. This is called double or triple melt VAR.

As explained by Choudhury *et al.* (1998), Seong *et al.* (2009) and Roskill Information Services Ltd (2013), the process melts a titanium electrode by use of a DC arc under a vacuum and an ingot solidifies in a water-cooled copper mould. To start the process, titanium sponge, scrap and alloying elements have to be compacted to an electrode. The electrode is then melted under a vacuum, producing a titanium ingot. The resulting ingot is then cleaned and remelted. This improves homogeneity and dissolution of the alloying elements. Aerospace quality ingots are often melted a third time. VAR accounts for about 80% of titanium melted worldwide (Roskill Information Services Ltd, 2013). The process of sponge to ingot production via VAR is shown in Figure 2.3.

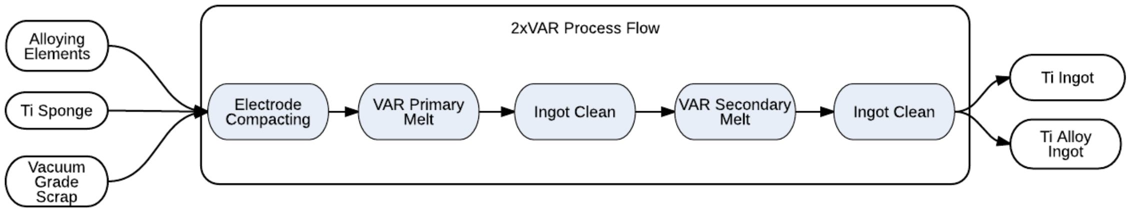


**Figure 2.3:** Vaccum Arc Remelting (VAR) Process (Sampath, 2005)

Another form of VAR is the non-consumable electrode melting (NC melting) method. In a direct melt NC furnace, loose feedstock is introduced into a retractable crucible. According to Roskill Information Services Ltd (2013), an advantage of NC melting is that temperatures which are considerably higher than the melting point of titanium can be achieved, thereby eliminating more contaminants in the first melt.

Choudhury *et al.* (1998) describes another variation of VAR, called vacuum arc double electrode remelting (VADER). In this method, two horizontal electrodes are used which are melted down to form the ingot. An arc is struck between the two, which melts the electrodes and the metal drops fall into a water-cooled copper mould.

A newer technology used to produce titanium melted products is cold hearth melting (CHM). CHM can be used to produce both ingots and slabs. It has become popular in recycling of titanium, because of its ability to remove contaminants in scrap (Roskill Information Services Ltd, 2013). Cold hearth melting can either be done by electron beams (EB) or by plasma arc torches (PA). Cold hearth melting is also a vacuum metallurgical process. The technology is used by RMI, Timet, ATI Allvac, Toho Titanium and VSMPO-Avisma and was approved as a production method for primary structures in military aircraft in 2003 (Roskill Information Services Ltd, 2013).

Dietrich *et al.* (1998) explains the process of cold hearth melting (or continuous flow melting) as a two-stage process, where metal is fed, melted and refined in a water-cooled copper trough, ladle or hearth. The metal is melted by use of two or three electron beam guns whose beams are split to sixty-four locations each, and which then move over the metal surface. In the second stage, solidification takes place in one of many round, rectangular or specially shaped water-cooled copper crucibles. The process flow for EB and PA CHM is shown in Figure 2.4.

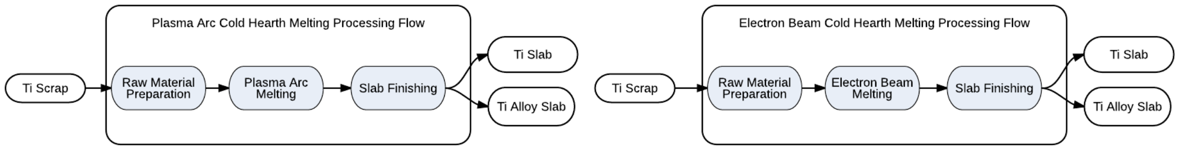


**Figure 2.4:** EB and PA CHM Process Flows (Sampath, 2005)

### 2.2.4 Titanium Mill Products

Once titanium ingots and slabs have been produced, they have to be processed to mill products, which are bought by fabricators. Mill products include products such as plate, sheet, billet and bar. Because of titanium's susceptibility to oxidation, surface removal operations are often required to eliminate surface defects, which results in large yield losses and expenses (Seong *et al.*, 2009).

Processing of titanium from ingot to mill product is the most expensive step in the production process, accounting for about 50% of the total production cost as seen in Figure 2.5 (Roskill Information Services Ltd, 2013). The cost associated with a titanium plate production facility is given in Table 2.5.

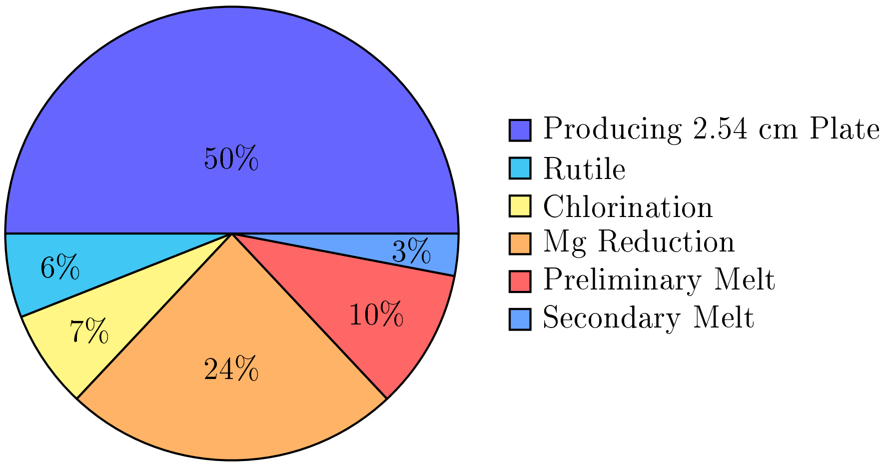


**Figure 2.5:** Cost Percentage per Process Step (Roskill Information Services Ltd, 2013)

## 2.3 Market Overview

The major players in the titanium production industry are illustrated in Figure 2.6. South African fabricators are marked by white diamond shapes. Titanium mill product producers are shown by gold stars, while known dedicated titanium recycling facilities are marked with a green circle. Gray squares indicate producers of ferrotitanium. The image helps

| Processing Step | Throughput [kg/h] | Equipment Cost |
|---|---|---|
| Beta Roll | 2 500 | $18 000 000 |
| Alpha Beta Roll | 2 500 | $0 |
| Anneal | 7 000 | $3 600 000 |
| Flatten | 7 500 | $540 000 |
| Clean | 10 000 | $72 000 |
| Section | 25 000 | $540 000 |
| Final Inspection | 5 000 | $180 000 |
| Total | - | $22 867 200 |

**Table 2.5:** Equipment Cost for a Titanium Plate Production Facility (Sampath, 2005)

to illustrate the large amount of titanium related companies in the East. The United States on the other hand dominates in dedicated recycling facilities. From the image the shipping distance from South African fabricators to scrap smelters also becomes clear. It is understandable why companies in South Africa choose to ship to India and sell their scrap at ferrotitanium price.


**Figure 2.6:** Map of Primary Titanium Related Companies Worldwide

### 2.3.1 Trade Statistics

In this section, an overview is given of South Africa's trade of titanium products. Its trade with mill products, waste and scrap, and ferrotitanium is addressed. The rise and fall of the titanium sponge price is discussed, along with reasons for its movement in price. To finalise, titanium ingot and mill product prices are given.

South Africa has a very small market share in titanium metal products. The import of titanium products is common. Figure 2.7 is compiled from import data obtained from the DTI (2016). It illustrates the relationship between imports of all titanium-containing products to South Africa since 1992. South Africa is a net importer of mill products, ferrotitanium and titanium scrap.

International Shipping codes from the Harmonised System was obtained from USITC (2016) to cross-reference shipping codes with that of the DTI. Code HS 8108 refers to titanium and articles thereof, including waste and scrap. Codes HS 8108.30 refers to waste and scrap titanium, but prior to 1996, HS 8108.10 referred to unwrought titanium, waste and scrap, and powders. To determine the import volume of titanium scrap, the values of HS 8108.10 were used where no data was available for HS 8108.30 (prior to 2002). HS 8108.20 is now used to indicate unwrought powders. It was not included in the graph, as very low volumes of powder are imported. HS 8108.90 indicates imports of other titanium articles. This includes titanium castings, blooms, sheet bars, slabs, other bars, rods, profiles, wire, plates, sheets, strips, foil, tubes and pipes. This is taken as titanium mill products, as the DTI does not indicate specifically which item of titanium is imported.

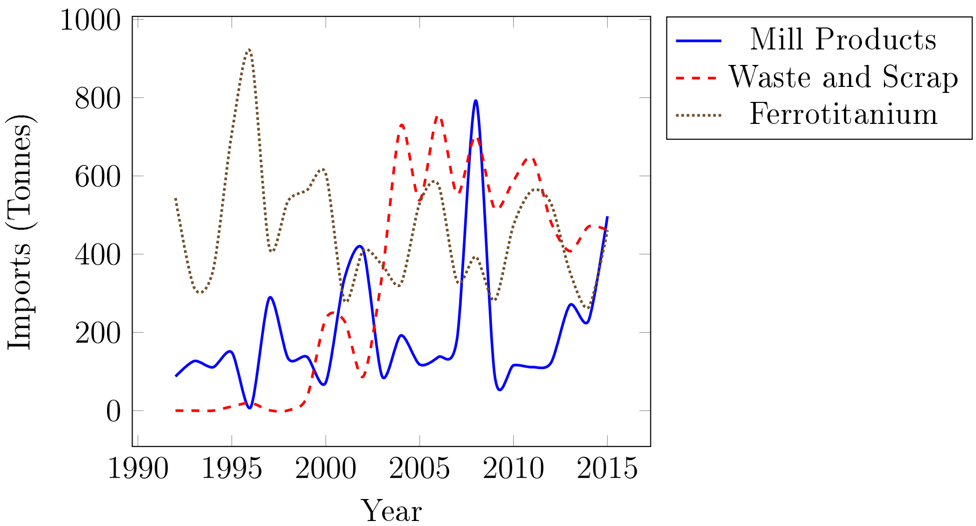


**Figure 2.7:** Imports of Titanium Metal Products to South Africa (DTI, 2016)

As can be seen from Figure 2.7, imports of titanium mill products are generally less than that of titanium scrap and ferrotitanium in the past 10 years. Since there are no large remelters of titanium scrap in South Africa, it can only be assumed that these large quantities of titanium scrap are used as alloying agent in the steel industry. According to Mosiane *et al.* (2011), titanium is imported as raw material for the production of stainless steels. This is likely the reason for the high amount of imports of titanium scrap and highly likely where the ferrotitanium imports are used. This exposes a large market for titanium scrap in South Africa. The trends of ferrotitanium and titanium scrap imports appear to be quite similar at times as well, which could provide more evidence that they are driven by the same market.

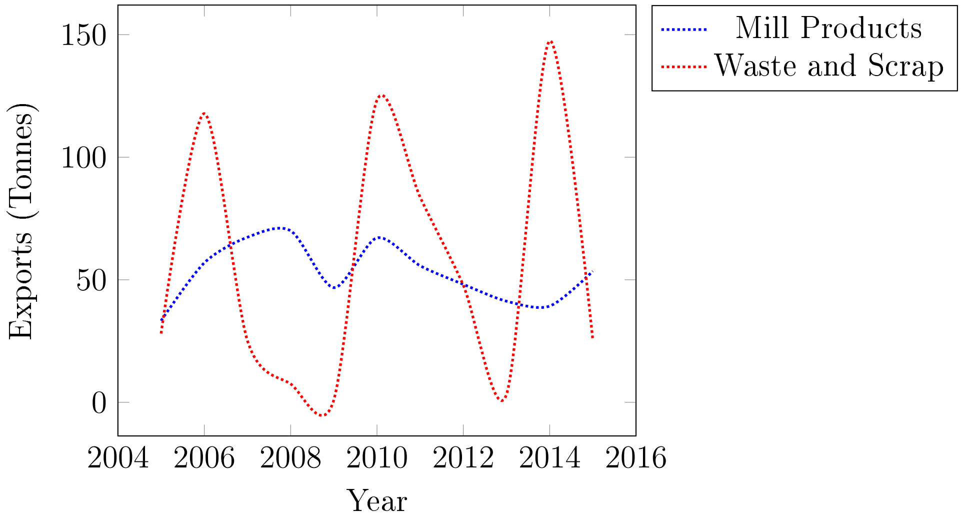


**Figure 2.8:** Exports of Titanium Metal Products from South Africa (DTI, 2016)

While the imports of titanium products to South Africa have much variance, the values are all between 0 and 1000 tonnes per annum. The same cannot be said for exports, where there are major outliers for waste exports and ferrotitanium exports. From 1997 to 2000, an average of 59.3 kt titanium scrap was exported per year. These values are outliers, as can be seen from Figure 2.8, where exports of titanium waste and scrap between 2005 and 2015 never exceeded 150 tonnes. Ferrotitanium exports in 2011 also reached 2.183 kt. It is unclear where this comes from, as South Africa imports ferrotitanium, as previously stated.

Exports of titanium mill products could be articles of titanium produced by companies such as Aerosud, Denel and Daliff. The volume of scrap exported in the past ten years varies between 0 and about 150 tonnes. An average of 55 tonnes per annum was exported between 2005 and 2015. This volume could provide encouragement to the prospect of titanium recycling in South Africa, as it is seen that a fair volume of scrap is available for recycling.

The inconsistency in exports of scrap is worrying. Years where only a few kilograms of scrap is exported could mean that there is no steady supply of scrap, proving recycling thereof infeasible. Ferrotitanium was not included in Figure 2.8, because the values of scrap and mill product exports are relatively small, when compared to the outlier year of 2011 for ferrotitanium.

## 2.3.2 Titanium Metal Prices

The price for titanium sponge has varied greatly through the years. Figure 2.9 shows the movement of the titanium sponge price from 1941 to 2010. Gambogi (2013) names some noteworthy reasons for the rise and fall of sponge prices.

In 1971 research into supersonic transport was terminated, which caused titanium prices to stay low. A peak in military aircraft production between 1975 and 1976 and increased orders of commercial aircraft between 1977 and 1981 caused a spike in the price. The collapse of the commercial aircraft market in 1982 was caused by an overestimation of the amount of aircraft which were ordered.

Titanium prices rose again from 1985 to 1989, as the commercial aircraft industry recovered and other markets began to emerge. Two sponge producers in the United States expanded their capacity because of this increasing demand in 1988 and 1989, but at the start of the 1990's, the end of the Cold War caused a cut in defense spending. The demand and price of titanium fell in response to this.

From 1990 to 1991, titanium consumption in the United States fell by 42%. In 1995, with the new application of titanium use in golf club heads, the demand rose again. Aircraft orders also increased in this period, leading to an all time high of 32 000 metric tonnes of titanium consumed in the United States in 1997. The Asian financial crisis caused cancellations of aircraft orders, resulting in a price drop in 1998. A low of 17 100 tonnes was seen in 2002 as a result of the September 11 terrorist attacks on America. This was followed by the sponge price, which dropped to $3.34 per pound in 2003.

The steel industry's use for titanium in stainless steels caused the price to rise again in 2004. The price rose steadily until the global financial crisis of 2008.

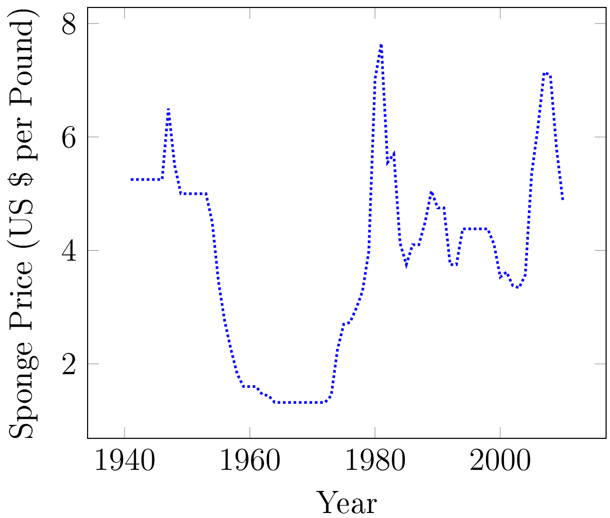


**Figure 2.9:** Titanium Sponge Price Through the Years. Compiled with data from Gambogi (2013)

Titanium ingot and mill product prices are obtained from Roskill Information Services Ltd (2013). It is said that the average melted products (ingot and slab) from Timet sold for $22.75 per kg in 2012. Mill products in 2013 sold for between $42 and $53 per kg.

## 2.4 Beneficiation of South Africa's Titanium Resources

Because South Africa ranks so high in mineral resource production, but no titanium metal is produced, many programs have been put in place to attempt to beneficiate the natural resources. This will help move South Africa up the value chain, creating greater value from its natural resources.

Currently South Africa has no titanium carbon-chlorination facility to produce titanium tetrachloride for use as feedstock in titanium metal manufacturing. According to CSIR (2016), the titanium beneficiation projects in South Africa started in 1999 with a foresight study by the Department of Arts, Culture, Science and Technology. A recommendation was made from the studies that research and development be done on titanium and titanium dioxide production, utilising local raw materials. In 2002, the Department of Trade and Industry's (DTI) Integrated Manufacturing Strategy and the Department of Science and Technology's (DST) National Research and Development Strategy was developed and used as the implementation strategy to the resource's beneficiation. This strategy was accepted by the South African government in 2003. In 2005, the Advanced Materials Initiative (AMI) was established and with it came the Light Metals Development Network (LMDN), focusing on aluminium and titanium. This was led by the Council for Scientific and Industrial Research (CSIR).

The Titanium Centre of Competence (TiCoC) was established in 2009, as support for titanium beneficiation grew. This project was created specifically to research and develop the technological basis which is required for a titanium metal industry in South Africa. The CSIR, supported by the DST developed a novel process to produce titanium powder. According to Maphango *et al.* (2013), approximately R200 million has been allocated to the project, with the pilot plant already operational and capable of producing 2kg per hour of titanium powder. The process is known as the CSIR-Ti process. Production of a semi-commercial test facility is due to start in 2017, which will be able to produce 500 tonnes of titanium powder per annum.

Various universities are assisting the TiCoC with technology development. Powder consolidation is done at the University of Cape Town (UCT) and Stellenbosch University (SU), high speed additive manufacturing at Cape University of Technology (CUT), high performance machining at SU, and friction welding at Nelson Mandela Metropolitan University (NMMU) (CSIR, 2016). Companies such as Aerosud are also assisting with high speed manufacturing, high performance machining, and sheet forming.

Rare Metals Industries (RMI), in partnership with the South African government, has completed a R50 million pre-feasibility study in Saldanha Bay for the RMI Speciality Metals Complex. Maphango *et al.* (2013) states that the project, which will require a total investment of about R20 billion, aims to produce 15kt per year of titanium when operating at full capacity. The plant is due to be commissioned by the end of 2017. Magnesium, zirconium and silicon products will also be produced by the plant. Table 2.6 shows a summary of the potential capacity and the planned yearly output of titanium related products from the RMI Speciality Metals Complex.

A study was completed by van Tonder (2010), who compared all the alternatives to the Kroll process to find the best method of beneficiating titanium minerals in South Africa. Twenty-six processes were compared, and the four leading processes, in terms of the techno-economic analysis performed were the CardQIT Process, ArmITP Process, the Kroll Process and the FFC Process. Surprisingly, the Kroll process, which was developed in the 1950's, still ranks as one of the best options to beneficiate titanium because of its

| Products | Capacity [tpy] | Output [tpy] |
|---|---|---|
| Titanium Sponge | 15000 | 3000 |
| Ferrotitanium | 2420 | 2420 |
| Seamless Ti Pipes | 1600 | 1600 |
| Ti Sheets | 3114 | 3114 |
| Ti Bars | 1600 | 1600 |
| Ti Slabs | 2076 | 2076 |
| Ti Belt | 600 | 600 |
| Ti Wire | 100 | 100 |

**Table 2.6:** Titanium Related Products which will be produced by the RMI Speciality Metals Complex (Primemetals, 2011)

commercial readiness and academic coverage on the process.

# Chapter 3

# Literature Review: Titanium Recycling

A general overview of the creation of titanium scrap and recycling thereof is given in this chapter. Global recycling statistics of titanium and a comparison to other metals is given to provide an idea of its relative recycling rate. There are many challenges specific to titanium recycling which are discussed. These include impurities or contaminants, the lack of readily available sponge, traceability and the volume of scrap available. A discussion of the current state of recycling is given, specifically with regards to the United States. The process of recycling from scrap sourcing to then melting to various forms are explained and their processes analysed, which makes up the theoretical background of the feasibility model. A discussion of novel and state-of-the-art recycling methods is given and in conclusion, a discussion of current and historical scrap prices is given.

## 3.1 Metals Recycling

Boulding (1966) described the state of the economy at that time as a transition between the so called "cowboy economy" of the 19th century and the future "spaceman economy", which we will reach by the latter end of the 21st century. In the 19th century, the economy was driven by exploitative tendencies, where resources were readily available for the taking. Consumption and production in this type of economy is seen as a good thing and success is measured by the amount of throughput in the system. This mindset still largely prevails in most parts of the world today. In contrast, the "spaceman economy" is aimed at minimising throughput. The success of the economy is not measured by production and consumption, but by maintenance of stock in the current system. These terms link closely with modern ideas of sustainability. Environmental and economic incentives are forcing manufacturers to reconsider what and how much they use to manufacture goods and think instead with a sustainable mindset.

At present, massive quantities of ore are extracted from the earth's crust to produce a small amount of metal. The conversion percentage of ore to metal is shown in Table 3.1, with platinum having the lowest conversion percentage with about 0.0005%. With the increasing demand for metal, more and more earth needs to be removed to satisfy the needs of the consumer. To make matters worse, the quality of ore is decreasing as well. The ore grade of copper, for example, has degraded from around 10% in the 19th century to about 0.47% in 2014 (Ayres, 1997; Brinninstool, 2015). This requires us to remove even more earth to obtain metals. Using our resources more sustainably through recycling is a solution to curb this trend and move closer to Boulding's "spaceman economy". This

| Metal | Metal Content [%] |
|---|---|
| Aluminium | 19 |
| Chromium | 10 |
| Copper | 0.4 |
| Gold | 0.0005 |
| Iron | 52 |
| Lead | 6.5 |
| Manganese | 33 |
| Nickel | 0.7 |
| Platinum | 0.0005 |
| Uranium | 0.002 |
| Zinc | 3.2 |

**Table 3.1:** Metal Content of Metal Ores (Ayres, 1997)

can create "closed-loop" material cycles where the current stock of metal is preserved. Every substance extracted from the earth's crust should be seen as a potential waste and materials should be recycled to as close as 100% as possible. Waste to resource strategies allow manufacturers to close the materials cycle in manufacturing. The general metals materials cycle is shown in Figure 3.1. It shows the life cycle metals go through, with process residues coming from all steps. By minimising the process residues at each step, the amount of material in the cycle is improved, and recycling efficiency is increased. This will result in a system where the dependencies on natural resources and mining operations are decreased and may be completely self-sustainable in the future. This study focuses exclusively on new scrap produced from the "Product Manufacture" step.

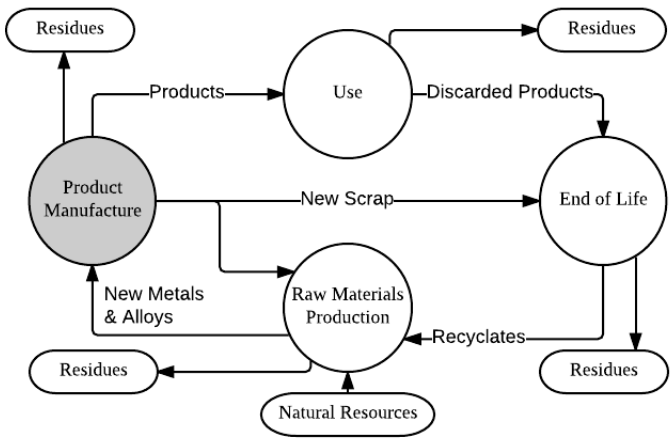


**Figure 3.1:** General Metal Material Cycle. Adapted from Graedel *et al.* (2011)

There are many factors which contribute toward reducing the waste residues in the materials production cycle. Reuter *et al.* (2013) conducted a study on the opportunities, limits and infrastructure for global metal recycling. The report determined those factors affecting metals recycling, as well as identifying opportunities, limiting factors and their consequences, infrastructure for optimising recycling, tools to aid in decision making, and policy drivers and recommendations. The identified recycling factors and infrastructure are used in this study as a guideline. The factors which influences metals recycling are:

- Recycling processes and physical and chemical influences on the metals and materials in the processing stream.
- Collection and pre-sorting.
- Physical properties and design of end-of-life products in the waste streams.

The first two factors are addressed in this study, but as the study is limited to new scrap recycling, end-of-life products are not relevant. The third factor is thus not addressed. Opportunities can be seen in all parts of the material life cycle where losses occur. Recycling of these losses presents an opportunity. Infrastructure which can assist in optimising recycling is listed as the following:

- Best Available Technique (BAT) standards
- Policy
- Knowledge
- Incentives
- Modelling

These opportunities, contributing factors and infrastructure suggestions are used as a guideline when assessing the recycling of titanium. The following section will assess the recycling rates of general non-ferrous metals worldwide. This helps to contextualise titanium recycling on a global scale.

### 3.1.1 Metals Recycling Rates

Graedel *et al.* (2011) conducted a study on the recycle rates of metals globally. Sixty metals were addressed in the study. Only the results of non-ferrous metals will be addressed, since this is the group titanium belongs to. End-of-life (EOL) recycling efficiencies, according to Graedel *et al.* (2011), can be measured in three levels, namely:

- The amount of EOL metal collected and re-entering the material recycling chain (Old scrap collection rate, CR).
- Efficiency of the recycling process (Recycling Process Efficiency Rate).
- EOL-Recycling rate (EOL-RR), either as pure metal or in an alloy (Functional Recycling).

Non-functional recycling refers to EOL-recycling where the metal is recycled, but becomes an impurity or tramp element in the new metal.

Figure 3.2 provides the flow of material in a metals recycling process. The process of primary refined metal production, fabrication of intermediate materials such as alloys and semi-fabricated parts and component manufacturing are seen in the squares in the first line. New scrap is created from the manufacturing process and enters the scrap market. Old scrap is collected after use, and also enters the scrap market. From here it is returned to the primary metal production and fabrication steps. Old scrap can also enter into non-functional uses and enter the material cycle for other metals (Metal B in

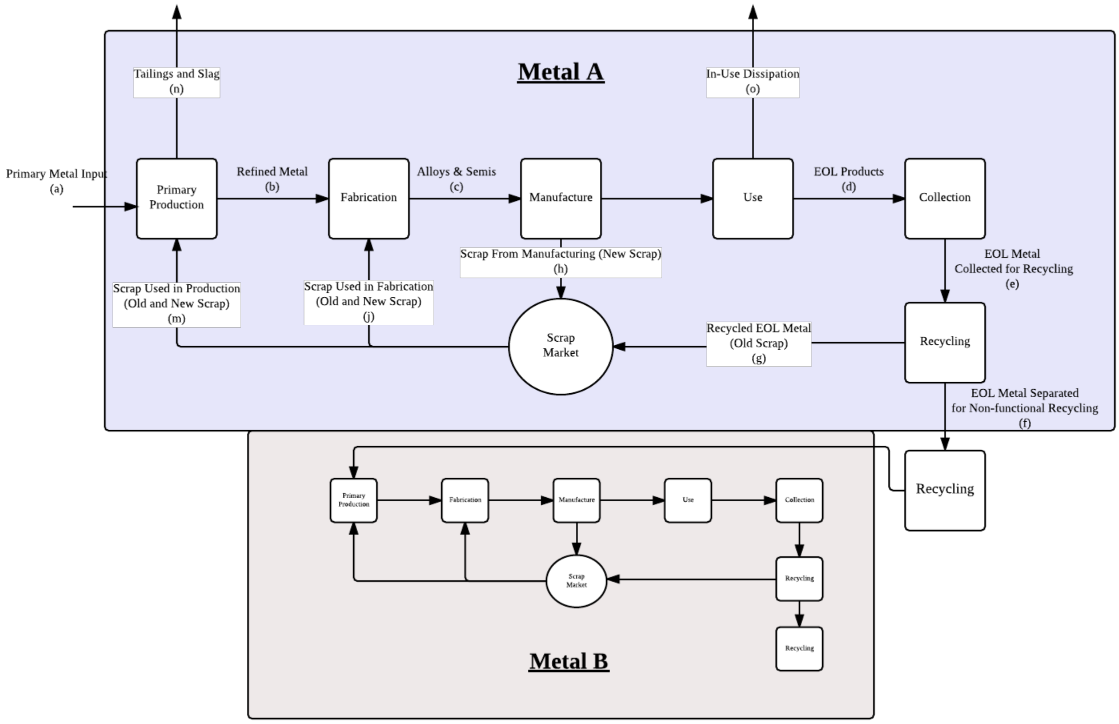


**Figure 3.2:** Metals Recycling Flow. Adapted from Graedel *et al.* (2011)

this case). An example of this is when copper is used in the production of alloy steel. In the case of titanium, this is seen when titanium scrap is used as ferrotitanium in stainless steel production. The old scrap recycling rate (CR), recycling process efficiency rate and EOL-RR are calculated using Equations 3.1.1 to 3.1.4, using letters as in Figure 3.2:

$$\text{CR} = \frac{e}{d} \tag{3.1.1}$$

$$\text{Efficiency Rate} = \frac{g}{e} \tag{3.1.2}$$

$$\text{EOL RR (Functional)} = \frac{g}{d} \tag{3.1.3}$$

$$\text{EOL RR (Non-Functional)} = \frac{f}{d} \tag{3.1.4}$$

Other important metrics in metal production include the recycling input rate (RIR) and the old scrap ratio. RIR is a description of the fraction of secondary scrap used in primary metal production. The RIR is the same as the recycled content (RC) in (c) if Equation 3.1.5 is used.

$$\text{RC} = \frac{(j+m)}{(a+j+m)} \tag{3.1.5}$$

Calculating RIR on a global scale is simple, but this is not the case when calculating it for a specific country. This is because the scrap percentage of an imported metal is not always known. The old scrap ratio (OSR) gives the fraction of old scrap in the recycling flow. It is calculated using Equation 3.1.6.

$$\text{OSR} = \frac{g}{(g+h)} \tag{3.1.6}$$

The old scrap ratio reveals both the old scrap recycled content and the quantity of old scrap which is reused in new products. Using these equations, the OSR, RC and EOL-RR have been calculated for 60 metals, providing a better understanding of the state of metals recycling in the world at present. Data was obtained from multiple sources, resulting in more than one result for some of the measurements. In these cases, an average was taken of the results. The results can be seen in Figures 3.3 to 3.5.

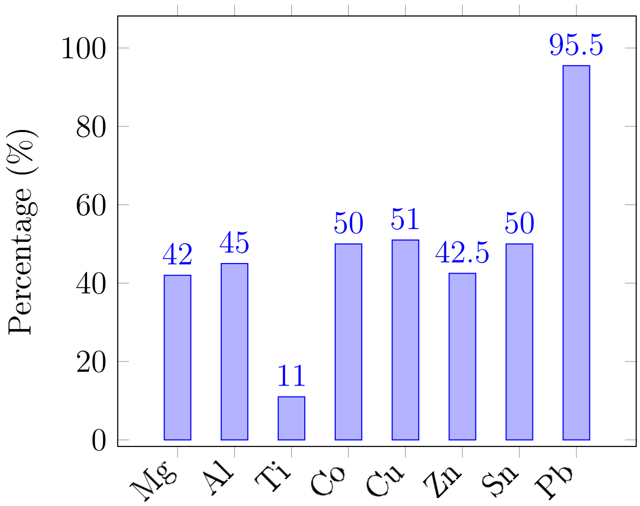


**Figure 3.3:** Old Scrap Rate of Non-ferrous Metals (Graedel *et al.*, 2011)

As can be seen from Figure 3.3, the old scrap rate for titanium is very low compared to other metals at 11%. The reason for this is that very little old scrap is recycled to titanium metal again, but instead is downgraded to ferrotitanium, and thus leaves the material cycle for titanium. Only about 2% of old scrap is used in titanium ingot production (Goonan, 2010).

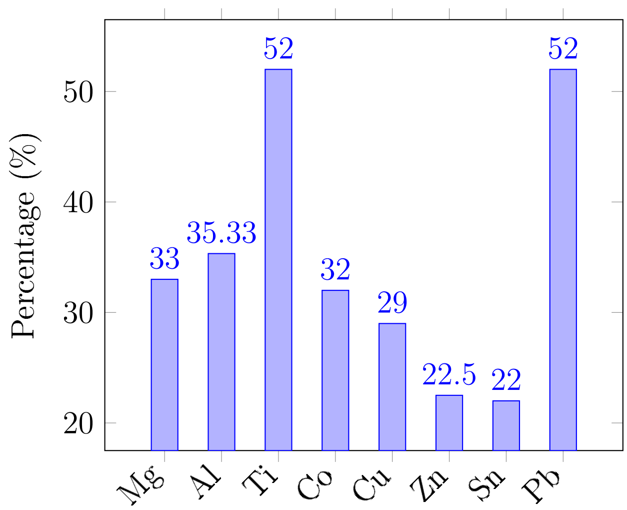


**Figure 3.4:** Recycled Content of Non-ferrous Metals (Graedel *et al.*, 2011)

The recycled content percentage of titanium ranks highest, level with lead at 52%. This is because of the large amount of new scrap used in the production of titanium ingots, where titanium sponge is melted together with new scrap. Large amounts of new scrap are available because of the high buy-to-fly ratio of aerospace components. This figure of 52% seems to be a bit misleading. As explained by Roskill Information Services Ltd (2013), the amount of scrap used in ingot production varied between 40% of ingot output in 2008 to 72% in 2009. The amount of scrap content in Timet's melted products was 51% in 2009, 41% in 2010 and 36% in 2011. Roskill Information Services Ltd (2013) deduces that the demand for titanium melted and mill products is linked with that of scrap, which increases as the other does. VSMPO-Avisma in Russia utilises between 23% and 25% scrap in their melts, while scrap generation in China is much less than in the United States and Europe, because they use the metal mostly for industrial applications. These applications generate much less scrap. This number will thus vary depending on the time and country from which the data is sourced.

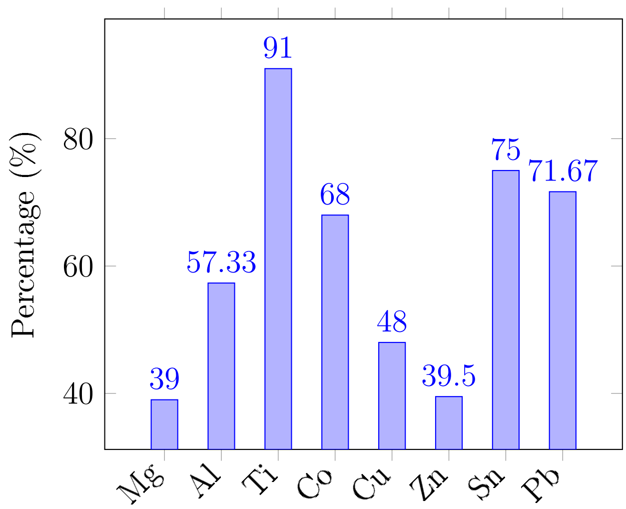


**Figure 3.5:** End-of-life Recovery Rate of Non-ferrous Metals (Graedel *et al.*, 2011)

The EOL-RR for titanium is very high. At 91%, very little is wasted. This value is for functional recycling, thus according to UNEP, the physical and chemical properties which made titanium desirable are retained in its new use. As previously stated, the majority of EOL titanium is used in ferrotitanium. While titanium's properties are still used in this application, it could be argued that this statistic is misleading, since so little is used in the production of titanium ingots. Goonan (2010) states that titanium old scrap is not effectively utilised because of its low usage in ingot production. A better definition is thus required, detailing the extent to which physical and chemical properties need to be used, to ensure consistency amongst scholars.

## 3.2 Current State

Currently, the majority of titanium scrap is either melted down together with titanium sponge during the production of titanium slabs or ingots, or it is downgraded to ferrotitanium, which is used in the steel industry. In 2014, 50 000 tonnes of titanium scrap metal were recycled in the USA (U.S. Geological Survey, 2015*a*). 11 000 tonnes were used in the steel industry, 1100 tonnes by the superalloy industry and 1000 tonnes in other industries (U.S. Geological Survey, 2015*a*). Figure 3.6 shows the amount of scrap recycled in the United States since 1992. Roskill Information Services Ltd (2013) states that about a third of titanium used for ferrotitanium production comes from process scrap, which this study investigates, while half comes from scrap from the production of mill products and the remainder from end-of-life products.

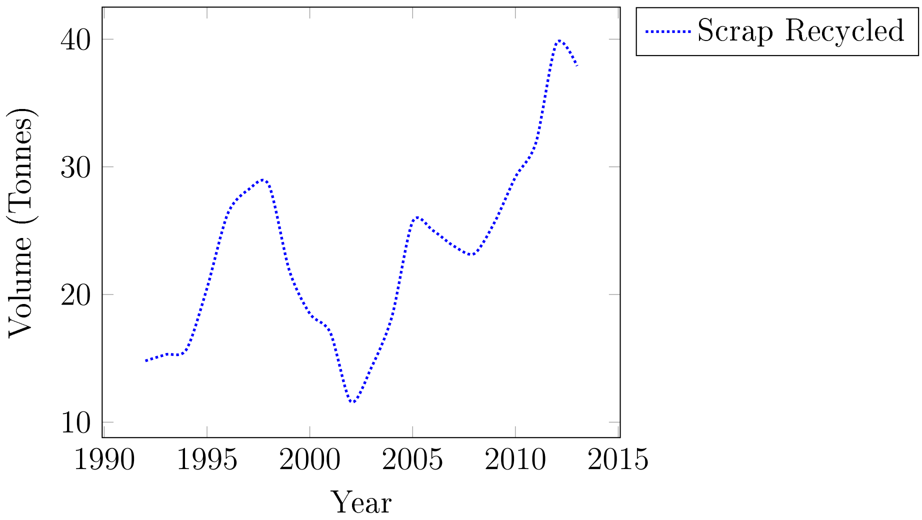


**Figure 3.6:** Titanium Scrap Recycled in the United States. Compiled with data from U.S. Geological Survey (1996, 1998, 2008, 2011, 2015*b*)

Figure 3.7 shows a Sankey diagram compiled using data from Goonan (2010). It illustrates the flow of titanium from ingot production to scrap use, measured in kilo tonnes. Of the initial 37 thousand tonnes, 25 are reduced to new scrap, either through mill product production or component fabrication. Of the 20 kt titanium used to produce components, 11 kt are reduced to new scrap, while 9 kt ends up being used in the components.

Of the initial 38 kt used to produce mill products, 14 kt are converted to scrap. Additional scrap input comes in the form of end-of-life components, contributing a further 3 kt in that year to the total supply of 28 kt available to recycle. Of this 28 kt stockpile, 22 kt are consumed within the United States, while the remainder is either unrecovered or traded with other countries. The steel industry consumed 7 kt of this, while the remainder was again used in primary ingot production.

## 3.3 Challenges in Titanium Recycling

Titanium has some specific challenges with regards to the quality and availability of scrap which can be used. Quality is influenced by impurities, which take the form of cutting fluids, carbide tool tips and other tramp elements in the scrap. Additional challenges such as the lack of a local sponge source and traceability of scrap are also addressed. As the local titanium fabrication business is relatively small, the amount of scrap available to recycle is also a challenge specific to South Africa, a discussion which is included in this section.

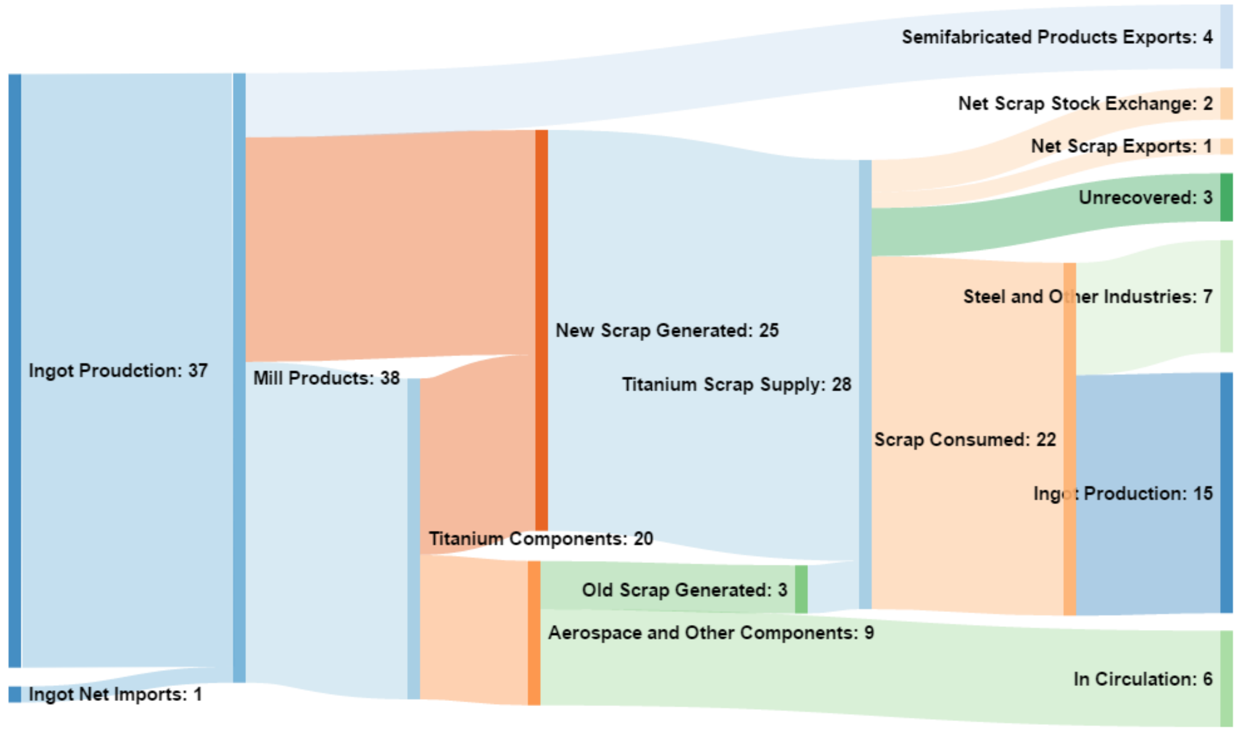


**Figure 3.7:** Material flow of Titanium in the United States in 2004. Compiled with data from Goonan (2010)

### 3.3.1 Impurities

One of the largest challenges in recycling titanium is the problem of impurities. The aviation industry requires strict tolerances on alloy compositions. When alloys have been contaminated with other elements, their structural integrity is compromised. There are two main types of contamination, namely high density inclusions (HDI's) and high interstitial defects (HID's), also known as hard-$\alpha$ inclusions (Bretherton *et al.*, 1990).

HDI's come from contaminants which cannot be absorbed during the melting process. Roskill Information Services Ltd (2013) describes high density inclusions as $\beta$ phase stabilised pieces of refractory metal. Examples include tungsten, tantalum or molybdenum, which have higher densities and melting points than that of titanium. HDI's are most often as a result of contamination by the cutting tool.

HID's occur because of molten titanium's tendency to react rapidly with many substances it comes into contact with; specifically oxygen, nitrogen and hydrogen (Roskill Information Services Ltd, 2013). These elements solidify the $\alpha$ phase, increasing the strength of titanium. In high concentrations, however, they lead to HID's, which consists of hard, brittle $\alpha$ phase areas (Roskill Information Services Ltd, 2013). According to Rotmann *et al.* (2011), nitrogen is picked up from nitrided scrap, carbon and hydrogen are picked up from lubricants, as water is a major component thereof.

One method of combating contaminants from lubrication fluid is by use of minimum quantity lubrication (MQL). MQL is an alternative lubrication method to traditional flood cooling. It is otherwise known as micro lubrication or near-dry machining. The method is used to cool and lubricate the cutting tool and work piece interface in machining. As the name implies, the method is concerned with using the minimum amount of cutting fluid, resulting in cost savings in the purchase and disposal of these fluids. Pressurised air is used to spray micro-scale droplets of cutting fluid onto the contact area.

The implementation of MQL brings many advantages over traditional flood cooling. In MQL, a more environmentally friendly vegetable oil or synthetic ester oil is used instead of the mineral oil used in flood lubrication, because very good lubrication properties are required (Woods, 2005). Not only does MQL have an economic advantage because of the reduced usage of coolant, but it has been shown to result in reduced tool wear compared to both dry and flood lubricated methods (Sreejith, 2008).

Unlike flood cooling, MQL is a form of consumption lubrication, as the majority of the fluid evaporates on contact when applied (Boubekri and Shaikh, 2015). The resulting system has a near dry work piece and produces swarf which requires no further drying or washing as the cutting fluid is evaporated. Since the amount of oil on the swarf is less than 1%, it can be introduced directly into the furnace when remelting, without any concerns over excessive smoke creation or melt losses (Schlesinger, 2013). This also means that there are no additional costs incurred with the disposal of cutting fluid, which is required in flood cooling. The vapour produced by the MQL operation does pose some health concerns. MQL cooling generates a large amount of mist compared to flood cooling, which needs to be properly ventilated (Boubekri and Shaikh, 2015). The effect of MQL on lubrication costs and quality of scrap produced is investigated in the background study.

### 3.3.2 Lack of Readily Available Sponge

Bretherton *et al.* (1990) states that the lack of readily available sponge is an issue with titanium recycling in the United Kingdom. As titanium scrap is mixed with raw sponge and re-introduced into the primary melt, a lack of a local sponge source means that imported sponge is required to recycle via this route. A similar problem is encountered in South Africa, where there is no sponge production capacity either. This may incur the requirement of imported sponge, especially when using traditional melting techniques such as VAR. Recycling of titanium scrap may thus only prove feasible once there is local sponge production capacity.

### 3.3.3 Traceability

Because scrap contamination is such an issue, the origins of scrap must be traceable to ensure that the metal has been kept separate from other metals and comes from a reliable source. Since the titanium metal industry in South Africa is so small, the origin of new scrap can be determined fairly easily. This is much more difficult when dealing with old scrap, but the scope of this project does not cover this. It is still important that the machining process, from which the scrap is sourced, be analysed thoroughly. This will determine whether the processing phase will be able to account for any additional trace elements in the mix.

### 3.3.4 Volume of Scrap

Justifying production of anything without sufficient raw material is difficult. If titanium scrap is seen as the raw material, there may not be a sufficient amount of scrap or a steady supply thereof to justify local recycling. Investing in dedicated titanium recycling equipment is infeasible if there is insufficient scrap to process to cover the equipment cost. The throughput capacity of any given recycling route must thus be available in a small enough scale to be feasible.

## 3.4 Scrap Sourcing

Scrap can be divided into three categories, namely home scrap, new scrap and old scrap (Veasey, 1993). Home scrap is generated locally by one's own manufacturing processes, recycled within the company itself. New scrap is also scrap generated as by-product of the manufacturing process, while old scrap is sourced from end-of-life products. New scrap and home scrap are desirable, as they generally have a higher quality, traceable origins and can be processed much faster than old scrap. Bretherton *et al.* (1990) divided scrap into three main forms, namely bulk-weldable, feedstock and chips. Pieces between 1kg and 200kg, originating from run-around, process scrap from the mill product manufacturer are called bulk-weldable scrap, as they can be welded into an electrode for consumable vacuum-arc melting. As South Africa has no capacity to produce titanium mill products, it cannot be sourced locally. Feedstock scrap is likely to be available in South Africa, but in relatively small quantities. Feedstock scrap usually weighs less than 1 kg and is sourced from component forging operations or from fabricators and consists of items such as rod ends, forging flashes, scrap blades or webbing scrap. The most common form of scrap, sourced from machining of titanium, is machine chips.

Possible sources in South Africa include aerospace companies named above, Aerosud and Denel, and biomedical companies, such as Southern Implants. Denel Aerostructures makes use of outsourced companies to machine some of their titanium parts. Cliff's Way Engineering, Daliff Engineering, Micromax Engineering and Pannonia Precision Engineering are listed as some of their local suppliers. These companies are all possible new scrap sources. At present, the majority of these companies export their scrap to countries such as India and the United States.

## 3.5 Scrap Processing

In this section the processing of titanium scrap is described in greater detail. Because of the stringent quality controls on titanium scrap, there is a required processing step which needs to be followed, before scrap can be melted down. This is done primarily to clean the scrap from contaminants such as cutting fluid leftover from the machining process. This section explains this processing phase for loose titanium machine chips, also referred to as swarf, and solid pieces of titanium scrap separately, as they undergo different processes.

### 3.5.1 Swarf Processing

Since this study deals with new scrap of only one titanium alloy, not much processing is required, when compared to old scrap batches containing mixed alloys. Once sourced, titanium scrap can undergo a processing phase to prepare the scrap for recycling. This helps to determine the quality of the scrap and remove some of the impurities discussed in Section 3.3. Titanium scrap which is to be recycled to critical applications such as the aerospace industry must undergo more processing as a higher standard of raw material is required.

The basic processing sequence of titanium scrap chips, according to Bretherton *et al.* (1990) and Kaplan and Ness (1987), is crush, wash or degrease, dry, magnetic separation, mix, chemical analysis, x-ray inspection and pack/store. This is illustrated in Figure 3.8. Scrap needs to be crushed, usually by hammermill, and degreased to remove cutting fluid on the chips. Crushers may be designed to perform both these tasks. Crushing the machine chips both improves handling and packing density in shipping. Chips are solvent-vapor degreased in trichloroethylene, which also removes some tramp impurities and foreign metal pieces. Any ferrous or ferromagnetic impurities remaining in the chips are then removed by magnetic separation. Chemical analysis is used to check for harmful contaminants and checks composition data to show levels of oxygen, iron and carbon, for example.

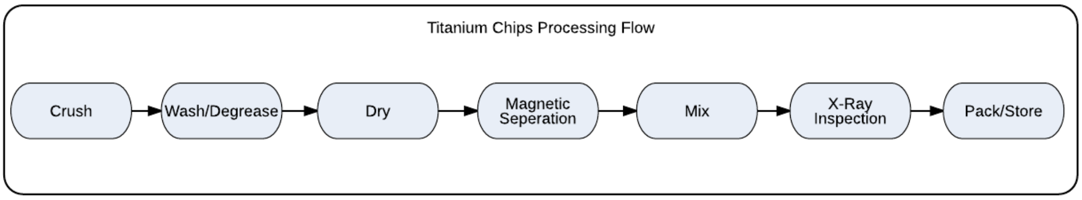


**Figure 3.8:** Titanium Chips Processing Flow (Bretherton *et al.*, 1990; Kaplan and Ness, 1987)

The large surface area-to-volume ratio of machine swarf makes it very prone to oxidation during melting. This means that a low amount of metal is recovered, while high energy input is required. Briquetting the loose swarf helps to reduce this surface area-to-volume ratio, improving melt yields, while also assisting in squeezing out any remaining lubrication fluid from the feed. Loose swarf is typically compacted under a pressure of about 30MPa (Schlesinger, 2013). An example of briquetted aluminium swarf is shown in Figure 3.9.

**Figure 3.9:** Machine Swarf Briquette

| Equipment | Investment Cost [ZAR] |
|---|---|
| Crusher | 650 000 |
| Washing | 700 000 |
| Drying | 150 000 |
| Magnetising and Conveyor | 400 000 |
| Screening | 250 000 |
| Briquetting | 800 000 |
| Total | 2 950 000 |

**Table 3.2:** Estimated Costs of Swarf Processing Plant

There is a potential for recycling flood lubrication cutting fluids using briquetting technologies. This helps reduce the amount of smoke and gasses generated in the melt while also reducing fumes produced from oxidation of smaller pieces of swarf. Some research has shown that there is no difference in the density of the briquette achievable by dry and wet swarf (Penchev *et al.*, 2015). Loose swarf is also difficult to handle and transport. Loose swarf has a density of about 0.25 g/cm$^3$, while briquetted swarf has a density of roughly 2 g/cm$^3$ (Puga *et al.*, 2009). Briquettes are uniform in size and thus easily transportable. Because briquettes are much denser, a higher quantity can be transported at a time when compared to loose swarf, resulting in more efficient transportation.

A quote was obtained from Granroth Engineering for a titanium scrap processing plant similar to the one described above, capable of processing an estimated 50kg swarf per hour. Table 3.2 shows the estimated costs for this equipment.

A system for degreasing titanium swarf for ferrotitanium production is described in detail in IPPC (2001). As the scrap is used in ferrotitanium, quality controls are not as stringent as those imposed when processing for use in primary titanium products. The system degreases swarf thermally, instead of chemically as in the process described above. Material is fed by conveyor belt and enters a rotary drier, which removes oil and water from the swarf. The oil is taken away by ducting, in the form of oil-bearing gas. This gas undergoes combustion in an afterburner. The clean scrap is collected in hoppers after degreasing and is ready for melting. The plant is very environmentally friendly, emitting only particulates, which are below 5mg/Nm$^3$ in size. Volatile organic compounds are destroyed in the afterburner. The plant requires waste fume dust to be recovered and disposed of in a landfill.

Consumption of utilities costs of such a plant are shown in Table 3.3 and its estimated investment costs required is shown below in Table 3.4 as quoted in 1998. This plant was commissioned in Rotherham, UK, by London & Scandinavian Metallurgical. The capacity of the plant is not given in IPPC (2001), but in Roskill Information Services Ltd (2013), there is a plant listed in this exact location, with a 25kt per annum ferrotitanium production capacity. This makes it the largest single producer of ferrotitanium globally, according to Roskill Information Services Ltd (2013).

### 3.5.2 Solids Processing

Solid new scrap parts are subjected to less processing. The pieces undergo magnetic separation, are analysed with X-ray spectroscopy, and are segregated by grade (Kaplan

| Utility | Usage |
|---|---|
| Gas | 374 $m^3$/tonne |
| Electricity | 180 kWh/tonne |
| Water | None Used |

**Table 3.3:** Estimated Utility Usages of Thermal Swarf Processing Plant (IPPC, 2001)

| Equipment | Cost [Million Euro] |
|---|---|
| Rotary Drier and Afterburner | 0.607 |
| Cyclone, Ducting and Filtration Plant | 0.410 |
| Total | 1.017 |

**Table 3.4:** Investment Cost of Thermal Swarf Processing Plant (IPPC, 2001)

and Ness, 1987). The remaining processing for solids is the responsibility of the melter, who may cut heavy pieces with a plasma torch, descale it by abrasion, clean it with caustic soda and pickle the surface with nitric acid containing some hydrofluoric acid (Kaplan and Ness, 1987). This is illustrated in Figure 3.10.

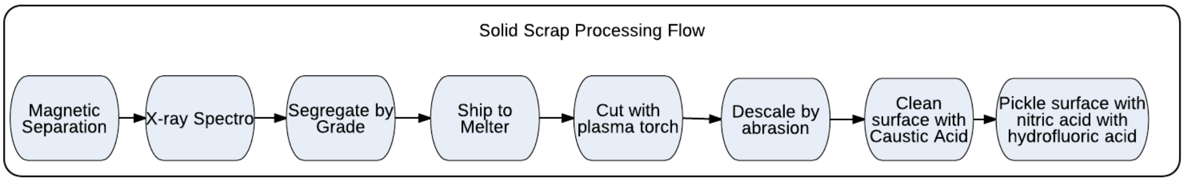


**Figure 3.10:** Titanium Solid Scrap Processing Flow (Bretherton *et al.*, 1990; Kaplan and Ness, 1987)

## 3.6 Melting of Titanium Scrap

Once processed, titanium scrap can be melted down again to a usable form. Melting technologies have already been explained in Chapter 2. This chapter will review these melting technologies with regards to their applicability in titanium scrap recycling.

### 3.6.1 Vacuum-Arc Remelting (VAR)

Bretherton *et al.* (1990) cites two problems with VAR in titanium scrap recycling. This method requires an electrode to be produced by compacting a combination of sponge, scrap and alloying materials and/or welding them together. Large, solid pieces of scrap can also be used as electrodes. Producing these electrodes creates considerable additional costs. Secondly, a refractory particle in the electrode may not be eliminated during the melting operation and may survive in the finished ingot. This means that an HDI which has been compacted into the electrode may fall into the molten pool and thus solidify in the finished ingot. This danger makes it difficult to recycle scrap using VAR, as it limits the quality of scrap that may be used and adds to the amount of scrap processing required.

| Processing Step | Throughput [kg/h] | Equipment Cost [USD] |
|---|---|---|
| Electrode Compacting | 7 000 | 5 400 000 |
| VAR Primary Melt | 400 | 7 200 000 |
| Ingot Clean | 1 000 | 540 000 |
| VAR Secondary Melt | 1 700 | 7 200 000 |
| Ingot Clean | 2 500 | 180 000 |
| Total | - | 20 520 000 |

**Table 3.5:** Cost of a VAR Plant to Produce Titanium Ingots (Sampath, 2005)

| Ti6Al4V Form | C [ppm] | O [ppm] | N [ppm] | H [ppm] | Al% | V% |
|---|---|---|---|---|---|---|
| Swarf (Before) | 400 | 2600 | 110 | 84 | 6.0 | 4.0 |
| Swarf (After) | 200 | 2700 | 110 | 22 | 4.4 | 4.2 |
| Solids (Before) | 1520 | 1520 | 75 | 22 | 6.0 | 4.0 |
| Solids (After) | - | 1320 | 76 | 15 | 4.8 | 4.1 |

**Table 3.6:** Chemical Composition of Titanium EB CHM refining (Dietrich *et al.*, 1998)

Choudhury *et al.* (1998) lists some of the advantages of VAR, which includes the removal of dissolved gases (such as hydrogen and nitrogen), minimising undesirable trace elements having high vapour pressures and removing oxides, and improving cleanliness. Table 3.5 shows equipment investment costs involved in the construction of a double VAR plant as estimated by Sampath (2005) to produce Ti4Al6V ingots.

### 3.6.2 Cold Hearth Melting (CHM)

Cold hearth melting is much more suited to recycle titanium than vacuum arc remelting. This is because it has some capabilities to remove impurities and refine scrap. During the first stage, when the metal flows over the trough, ladle or hearth, a skull is formed, over which the molten metal flows. HDI's sink and are entrapped in this skull (Bretherton *et al.*, 1990; Dietrich *et al.*, 1998). HID's (hard $\alpha$ inclusions) can be dissolved by CHM's ability to achieve superheat and the resistance time in the molten pool as these inclusions have a high melting point (Bretherton *et al.*, 1990; Roskill Information Services Ltd, 2013).

Dietrich *et al.* (1998) states that impurities which have lower densities than the molten pool can be segregated by flotation. 3.6 shows the refining capabilities of EB CHM on Ti6Al4V scrap swarf and solids to produce an ingot size of 150 mm, weighing 62.6 kg, using a trough size of 120 mm by 300 mm, as determined by Stephan (1974).

As can be seen in the Table 3.6, losses occurred to some of the alloying elements. Bretherton *et al.* (1990) explains that this happens because the process is done under a hard vacuum and some vaporisation losses occur. This is a troublesome aspect of titanium recycling which CHM does not overcome, however these losses can be optimised. Because of these losses, careful blending needs to take place before the melt to ensure the final alloy confirms to specifications.

Vutova *et al.* (2010) conducted a study to determine these optimum melting parameters for refining titanium scrap using EB drip melting and determined that material

| Processing Step | Throughput [kg/h] | Equipment Cost [USD] |
|---|---|---|
| Raw Materials Preparation | 7 000 | 180 000 |
| Electron Beam Melting | 700 | 18 000 000 |
| Slab Finishing | 6 000 | 180 000 |
| Total | - | 18 360 000 |

**Table 3.7:** Cost of an EB CHM Plant to Produce Titanium Slab (Sampath, 2005)

| Processing Step | Throughput [kg/h] | Equipment Cost [USD] |
|---|---|---|
| Raw Materials Preparation | 7 000 | 5 400 000 |
| Plasma Arc Melting | 450 | 14 400 000 |
| Slab Finishing | 6 000 | 180 000 |
| Total | - | 19 980 000 |

**Table 3.8:** Cost of a PA CHM Plant to Produce Titanium Slab (Sampath, 2005)

losses of less than 1% and oxygen concentration less than 400 ppm can be achieved using between 11.5 kW and 12 kW beam power and between 0.09 mm/s and 0.14 mm/s casting velocity. The study found that optimal titanium scrap refining takes place at 11.25 kW EB power and 0.0835 mm/s casting velocity. In a study by Georgiev *et al.* (1990) to reduce oxygen content in titanium scrap using EB drip melting, it was found that optimum conditions are at 2370 K for an overall time of 6 minutes. Beam power was in the range of 1.5 kW.cm$^{-2}$ to 3 kW.cm$^{-2}$ and feeding velocity was between 0.15 cm.min$^{-1}$ and 0.9 cm.min$^{-1}$. These experiments were carried out using EB drip melting, meaning the metal was not run over a water-cooled hearth to refine it of HDI's and was melted directly into an ingot.

EB cold hearth melting furnaces are able to produce direct cast of both ingots and slabs, resulting in flexibility and sometimes in cost savings as the intermediate step of ingot production step can be left out (Roskill Information Services Ltd, 2013). Table 3.7 shows estimated equipment investment costs involved in a EB CHM plant for producing Ti6Al4V slab from Sampath (2005).

Another type of cold hearth melting is plasma arc CHM, which uses a plasma torch as its heat source. PA CHM overcomes the problem of losses of alloying elements according to Bretherton *et al.* (1990). The estimated costs of a PA CHM processing plant, which produces Ti6Al4V slabs, are given in Table 3.8 (Sampath, 2005).

### 3.6.3 Induction Skull Melting (ISM)

The final melting technology used in the production of titanium metal products is induction skull melting (ISM). ISM is not used widely for titanium, but has some advantages for scrap recycling. Roskill Information Services Ltd (2013) lists some of the advantages as follows: virtually any scrap can by used, almost any alloy can be produced, long resistance times leads to remelting, dissolution of most particles with a high melting point and surviving inclusions are entrapped in the mushy layer between the liquid and the solid skull, and the ingot can be cast in any shape. Tifast in Italy and VSMPO in Russia make use of ISM furnaces (Roskill Information Services Ltd, 2013).

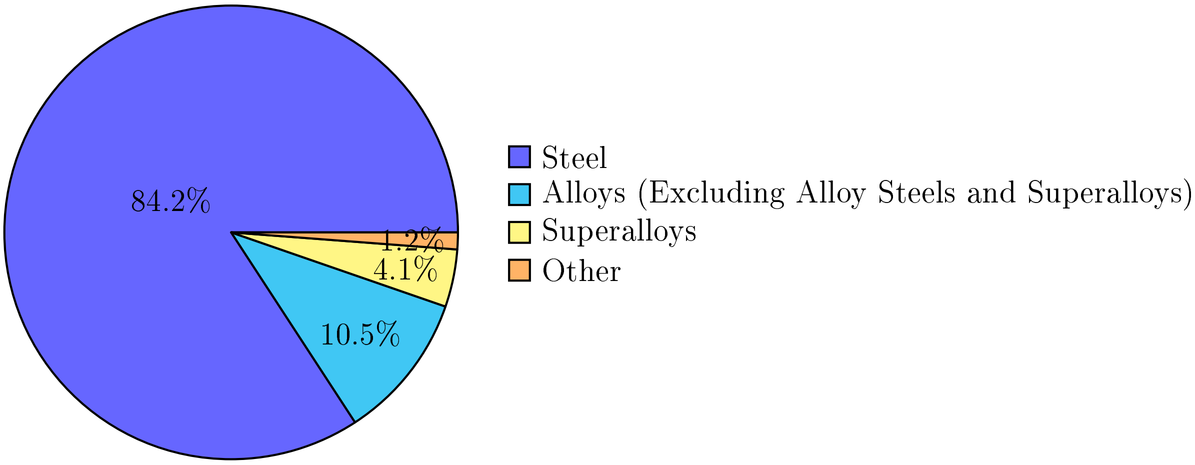


**Figure 3.11:** End-use Areas of Ferrotitanium in the United States (Bedinger *et al.*, 2013)

### 3.6.4 Titanium Investment Casting

Casting of titanium is difficult because of the very high requirements on the moulding materials. The mould should have very high thermal stability, no deformations and should not be chemically reactive (Karwiński *et al.*, 2011). Nevertheless, titanium golf club heads, jewellery and implants are sometimes produced from investment casting of titanium. Klotz and Heiss (2016) conducted a study to determine the best crucible to use when casting titanium. Four materials, namely zirconia coated quartz, yttria coated aluminium titanate, a ceramic shell crucible with a yttria coating and a bulk yttria crucible were used. The study concluded that high quality yttria or yttria alumina crucibles are required when casting titanium jewellery. Klotz and Heiss (2016) also states that crucibles can only be used once when creating large titanium castings. These expensive crucibles restricts the use of titanium investment casting. The benefit of titanium casting is that it results in a near-net shape component, resulting in reduced material wastage (Roskill Information Services Ltd, 2013). Some precision casting furnaces are capable of using titanium scrap as source material, which means this is a method worth exploring (ALD Vacuum Technologies, 2016).

### 3.6.5 Ferrotitanium

The alternate recycling route of titanium is to use it as alloying agent for the steel and aluminium industries. This usually takes the form of ferrotitanium or ferro-silico-titanium. When ferrotitanium is used as an alloying agent, it increases yield strength and reduces the tendency to crack. In steelmaking, titanium is used for deoxidation, grain-size control, and carbon and nitrogen control and stabilisation (Bedinger *et al.*, 2013). Figure 3.11 shows the distribution of end uses for ferrotitanium. It can be seen that over 84% is used in the steel industry.

The production of ferrotitanium is explained in IPPC (2014) and the process is shown in Figure 3.12. The process starts with raw material in the form of lump scrap metal castings, wrought products and machine swarf. The raw material then undergoes processing, similar to that described in Section 3.5. Once large pieces have been cut to size and swarf has been pulverised, degreased and dried, the titanium is weighed into pans with ferrous scrap and fed into an electric induction melting furnace. Ferrotitanium ingots are then cast and transferred to other operations for crushing, breaking, grinding, sieving and packing. Ferrotitanium is graded into two categories namely 30% or 70% titanium (Bedinger *et al.*, 2013).

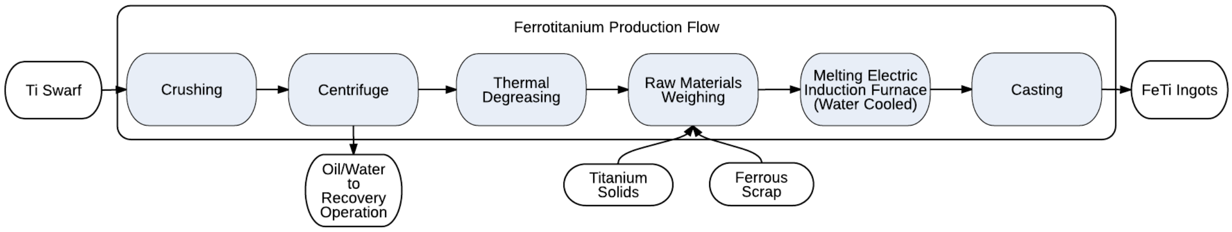


**Figure 3.12:** Process Flow of Ferrotitanium Production (IPPC, 2014)

Basson *et al.* (2007) performed a study on South Africa's ferro alloy industry, in which no mention is made of current ferrotitanium production in South Africa. The research does state that ferrotitanium was produced, amongst other alloying materials, in Vereeniging, Transvaal, but the production plant was closed down in 1953. A study was done by Slatter and Barcza (1987), to explore the possibilities of ferro-alloy production in South Africa, among which ferrotitanium was considered. Attempts were made to produce 70% ferrottianium, using a 200 kW D.C. transferred-arc plasma furnace. The produced ferrotitanium had a composition of 56.4% titanium, 14.5% iron, 21.8% silicon and 13.5% aluminium. The study concluded that the cost of producing the ferrotitanium is not economically viable without an adequate supply of titanium scrap, which can be bought at a reasonable price. Production of ferrotitanium, with titanium content between 30% and 40%, was found to be the most economically viable. Production thereof in a sealed furnace on large-scale required further investigation.

According to Bedinger *et al.* (2013), the largest producers of ferrotitanium in 2013 were India, Russia and the United States. Roskill Information Services Ltd (2013) differs from this, stating that the world production of ferrotitanium in 2013 was about 100kt, with the largest producers being the United Kingdom, Russia and China producing 20ktpy, 15ktpy and 50ktpy respectively. The United Kingdom uses imported scrap as its main source to produce ferrotitanium. A summary of the largest ferrotitanium producers in the world, according to Roskill Information Services Ltd (2013) is given in Table 3.9.

## 3.7 Powder Technology

The high buy-to-fly ratio of aerospace titanium parts results in large volumes of titanium being wasted. Titanium powder metallurgy (PM) allows products to be produced at near-net shape, resulting in less wastages, and expensive production equipment, which is used to produce ingots and mill products, to be cut out. There are many processes for producing titanium powder, such as chemical reduction, hydride-dehydride, gas atomization, plasma-rotating electrode and mechanical alloying (Moll and Yolton, 1998). The only commercial process used to convert titanium scrap to powder is the hydride-dehydride (HDH) process.

| Company | Location | Capacity [ktpy] |
|---|---|---|
| Armenia | | |
| Armenian Titanium Production | Yerevan | 3.6 |
| China | | |
| CITIC Jinzhou Ferroalloy | Jinzhou City, Liaoning | 2.0 |
| Hebei LuyiXian Ferro Alloy | Hebei Province | 2.0 |
| Hebei Jindu Ferroalloy | Qinghe County, Hebei | 3.0 |
| Jiangyin ReDe Alloys Material | Jiangyin, Jiangsu | - |
| Jilin Province Dongfeng Iron Alloy | Dongfeng, Jilin | - |
| Jinzhou Hengli Ferroalloy | Jinzhou City, Liaoning | 3.6 |
| Metalink International | Nanjing, Jiangsu | 1.0 |
| Sunstone Carbon | Beijing | - |
| Other | Various | 8.0 |
| India | | |
| D.S. Alloys | Delhi | 0.8 |
| Essel Mining & Industries | Vapi, Gujarat | 1.2 |
| Russia | | |
| VSMPO-Avisma | Verkhnaya Salda, Sverdlovsk | 10.0 |
| Klyuchevsky Ferroalloy Plant | Dvurechensk, Sverdlovsk | 10.0 |
| Ralfement AG | Kostroma | 1.8 |
| Ukraine | | |
| Zaporozhye Titanium & Magnesium | Zaporozhye | 6.0 |
| UK | | |
| London & Scandinavian Metallurgical | Rotherham | 25.0 |
| F.E. Mottram | Congleton, Sheffield | 6.1 |
| Ferro-Ti & Alloys | Burton-on-Trent | 5.0 |
| Tivac Alloys | Rotheram | 5.0 |
| USA | | |
| RTI Alloys | Canton, OH | 7.3 |

**Table 3.9:** List of Primary Ferrotitanium Producers (Roskill Information Services Ltd, 2013)

### 3.7.1 Hydride Dehydride Process (HDH)

The HDH process is based on the reversible interaction between hydrogen and titanium seen in the formula below.

$$\mathrm{Ti} + \mathrm{H_2} \rightleftarrows \mathrm{TiH_2} \tag{3.7.1}$$

Moll and Yolton (1998) explains the principles of the HDH process as follows: Titanium has a very high affinity for hydrogen and can thus be easily hydrogenated by heating it in a hydrogen atmosphere. This is illustrated in Figure 3.13. The brittle hydrogenated titanium can then easily be crushed to a fine powder. After it has been crushed, the hydrogen can be removed by heating the powder in a dynamic vacuum. Titanium hydrogenation of pure titanium is more or less 400℃ at 1 psi positive hydrogen pressure. Moll and Yolton (1998) states that machine turnings can be hydrogenated in four hours. According to McCracken *et al.* (2011), titanium takes on hydrogen in excess of 650℃ and is dehydrated above 350℃. Nearly any source of titanium can be used in the HDH process, as long as it is clean and below 5cm in thickness (Qian and Froes, 2015).

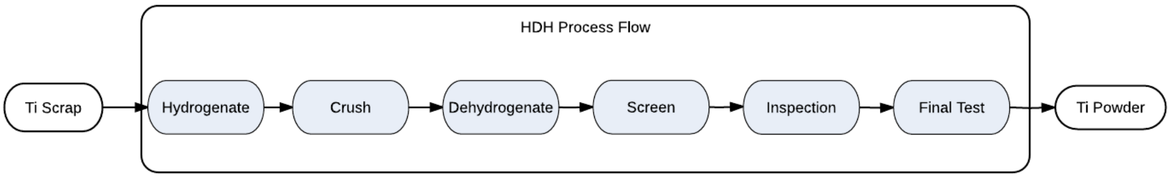


**Figure 3.13:** HDH Powder Production Process (Moll and Yolton, 1998)

Dawes *et al.* (2015) lists four key process variables in powder production, namely particle morphology, particle size distribution (PSD), bulk packing and flow properties, and chemical composition. These process variables all influence the quality of the final part produced from the powder and the types of applications it can be used for.

Particle morphology is the study of the shape of the powder particles. Particles are classified as either spherical or non-spherical in powder metallurgy. Spherical particles are more likely to be packed more efficiently than irregular powder particles (Karapatis *et al.*, 1999). In additive manufacturing, the powder bed packing density is significantly influenced by the particle morphology, which directly influences the density of the final part (Gibson *et al.*, 2010). The HDH method produces highly irregular particles, which is reflected in its lower selling price. According to Moll and Yolton (1998), HDH powder is angular and cold compaction and sintering or isostatic pressing can be used for densification thereof. McCracken *et al.* (2011) analysed the morphology of powder produced by the HDH method using titanium sponge and commercially pure titanium as feedstock material. They found that powder produced using the Hunter process sponge resulted in highly porous powder, while Kroll sponge resulted in semi-porous particles. Particles produced from commercially pure titanium (ingot and wrought feedstock) had no internal porosity. Scrap titanium is expected to have similarly low porosity. HDH powder can be converted to spherical powder form by a process called induction plasma spheroidization (Froes, 2012).

The particle size distribution is the range of particle sizes in a powder batch. The PSD in electron beam melting (EBM) is usually between 45 $\mu$m and 106 $\mu$m, while selective laser melting uses particles in the range of 15 $\mu$m to 45 $\mu$m (Dawes *et al.*, 2015). The HDH method produces particles in the range between 45 $\mu$m and 500 $\mu$m according to Dawes *et al.* (2015), while Roskill Information Services Ltd (2013) states that the range is 50 $\mu$m to 300 $\mu$m. Particles which are finer than 45 $\mu$m are very sinter-reactive and are difficult to recover after dehydrogenation. This limits the yield of powder with particles of this size (McCracken *et al.*, 2011).

Of greatest importance in the chemical composition in titanium powders are inclusions of nitrogen (N) and oxygen (O). Payne *et al.* (1997) produced a powder form of the Ti6Al4V alloy by the HDH method. The alloy's composition is shown in Table 3.10. McCracken *et al.* (2011) states that oxygen content per weight% increases exponentially as particle size decreases, because of the increase in surface area to volume ratio. Oh *et al.* (2014) conducted a study on the production of low oxygen titanium powder from scrap via the HDH method and deoxidation process. Scrap from Ti-Mo and Ti-V alloys was used and produced powders with 3230 ppm and 3090 ppm oxygen respectively. The powder was then deoxidised in the solid state (DOSS) and reduced the oxygen content to

| Element | Content % |
|---|---|
| Al | 5.09 |
| Cu | <0.01 |
| Fe | 0.1 |
| Sn | 0.01 |
| V | 4.17 |
| Nb | 1.17 |
| Mo | 0.01 |
| W | 0.01 |
| Cr | 0.02 |
| Si | 0.02 |
| C | 0.02 |
| H | 0.0015 |
| N | 0.0060 |
| O | 0.1310 |

**Table 3.10:** Chemical Composition of Ti6Al4V HDH powder (Payne *et al.*, 1997)

1000 ppm and 870 ppm respectively. Compared to commercial powders which have oxygen contents of 2750 ppm and 3340 ppm respectively, the oxygen content of the produced powders can be seen as considerably low. A similar experiment was carried out by some of the same researchers using the alloy Ti-Mo-Si and reduced oxygen content from 3350 ppm to 1700 ppm (Oh *et al.*, 2015).

Azevedo *et al.* (2003) investigated an alternate route for the HDH process of Ti-6Al-4V powder production. The normal route of hydrogenating, milling, dehydrogenating, pressing and sintering was changed to a process where sintering and dehydrogenation takes place in a single step to reduce processing time and save energy. Al, C, Fe and V contents were in accordance with ASTM B 265-90 grade 5 standard, as was the final hydrogen content. The final oxygen content was beyond the upper limit for the standard.

Goso and Kale (2011) produced titanium metal powder at Mintek by using the HDH process. Titanium sponge was used as the raw product to produce the powder at laboratory scale. The sponge was hydrogenated in a horizontal tube furnace for two hours at 600℃, milled using planetary and roller mills, and then dehydrogenated in a vacuum retort and fitted in a muffle furnace for 36 hours at 700℃. Particle sizes had a mean of 27.74 $\mu$m and 41.84 $\mu$m when milled with the planetary and roller mills respectively. The produced powder had too high a carbon content to match specifications for commercial powder, but was found suitable for the production of powder metallurgical compacts. Another experiment involving titanium powder production from waste was done by Chhiba (2012) at the University of Cape Town. The research involved the design of a ball mill capable of crushing and hydrogenating the powder simultaneously. Experiments were done utilising both commercially pure and Ti-6Al-4V waste machine turnings. A laboratory scale 1.3 $l$ ball mill, with operating capabilities of under 200 kPa hydrogen, was built and successfully used to create hydrogenated titanium powder.

## 3.8 Novel and State of the Art in Titanium Recycling

The IME process is a method of recycling and refining contaminated turnings, which are downgraded to ferrotitanium at present. Rotmann *et al.* (2011) describes the process as a combination of conditioning, vacuum induction melting (VIM) and vacuum-arc remelting (VAR) processes. The conditioning step consists of a cleaning stage, which entails drying the turnings in an oven at 120℃ to evaporate water, followed by a wash in ethanol to remove oil-based lubricants and dried again at 100℃. Following this the turnings, a mixture of Ti-6Al-4V and Ti-6Al-2Mo-4Zr-2Sn-Si, were compressed into briquettes of 300g and a density of 1.5 $kg/dm^3$. A final heating to 400℃ was done to ensure the removal of organic compounds before the VIM step. The VIM stage involved a homogenisation and a deoxidation step to ensure a consistent melt and remove oxygen contamination. A final step of VAR is added to create a refined titanium electrode from the titanium ingot produced in the VIM step. The author of the paper makes the case for a new specification in titanium alloys, which could see the rise of low cost titanium to be used in automotive, healthcare and chemical engineering applications. The IME process has successfully been applied to recycle titanium-aluminide scrap and Ti-6Al-4V (Friedrich *et al.*, 2007, 2009; Reitz *et al.*, 2011). An intermediate step of electroslag remelting (ESR), between the VIM and VAR steps is included in these studies.

## 3.9 Scrap Prices

Historically, titanium scrap prices are quite erratic. According to Roskill Information Services Ltd (2013), scrap prices are driven by the ferrotitanium market demand and, to a lesser extent, by the ingot market. The immediate demand for scrap is also a factor in the price. Depicted in Figure 3.14 is the low and high prices for titanium scrap between 1993 and 2013. The steep price hike in 2005 was caused by a combination of a shortage of scrap and an increase in sponge prices.

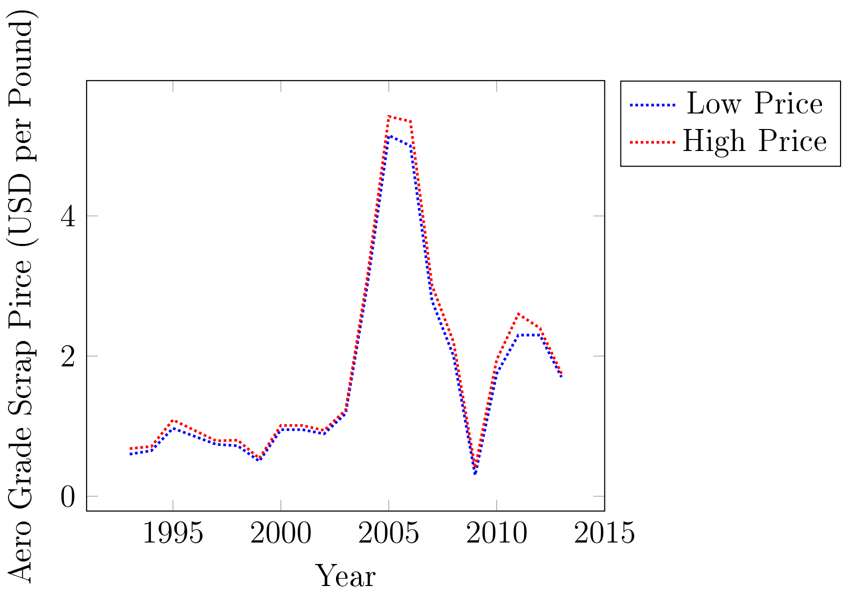


**Figure 3.14:** Titanium Scrap Prices Since 1993. Compiled with data from Roskill Information Services Ltd (2013)

The prices for various qualities of titanium scrap metal at the time of the study are shown in Table 3.11. Bulk weldable and clips are worth more, since they require less processing and qualify as solid scrap. Commercially pure (CP) solids are worth less, as they are not alloys such as Ti-6Al-4V and have less desirable qualities. Ingot quality chips are those typically produced by Denel and Aerosud, but are sold at a price similar to that of ferrotitanium quality chips to be used in stainless steel production.

| Product | Cost [USD/kg] |
|---|---|
| Ti-6Al-4V Bulk Weldable Scrap | 6.85 |
| Ti-6Al-4V Ingot Quality Chips | 4.11 |
| FeTi Quality Chips | 0.64 |
| CP Solids | 3.49 |
| Ti-6Al-4V Clips | 6.05 |

**Table 3.11:** Unprocessed Titanium Scrap Prices of Various Qualities (Metalprices.com, 2016)

Processing titanium turnings to clean briquettes adds about 1.23 USD per kilogram to the price according to industry experts who chose to remain anonymous. In addition to this, as previously mentioned, the briquetting operation allows scrap to be compacted considerable tighter, allowing a larger mass to be transported per shipment. This is particularly relevant in South Africa, as scrap will have to be shipped across large distances to be melted. Solids, clips and ferro-quality turnings gain 0.7 USD per kilogram once processed.

# Chapter 4

# Literature Review: Cost Modelling

There are many types of feasibility studies, but this study is mainly concerned with economical feasibility. According to Green and Perry (2008), there are eleven financial information requirements which fit within an economic feasibility study. These are summarised below:

- Fixed Capital Investment
- Working Capital Investment
- Total Capital Investment
- Total Manufacturing Expenses
- Packaging and In-plant Expenses
- Total Operating Expenses
- Marketing Data
- Cash Flow Analysis
- Project Profitability
- Sensitivity Analysis
- Uncertainty Analysis

These requirements are discussed in greater detail in this section and form the basis of this study's financial models. This section completes a comprehensive literature study on methods used in the industry to estimate investment costs for production plants. the content of the section is sourced from a combination of Turton *et al.* (2008), Ruhmer (1987), Green and Perry (2008), and Silla (2003). Similar methods are described by all these sources, and those relevant to the study are summarised in this section. In this chapter, capital investment costs, manufacturing costs, economic analysis, profitability analysis and uncertainty analysis are discussed in detail.

| Class of Estimate | Level of Project Completion [%] | Typical Purpose of Estimate | Methodology (Estimating Method) | Expected Accuracy Range [+/- Range Relative to Best Index of 1] | Preparation Effort [Relative to Lowest Cost Index of 1] |
|---|---|---|---|---|---|
| Class 5 | 0 to 2 | Screening or Feasibility | Stochastic or Judgement | 4 to 20 | 1 |
| Class 4 | 1 to 15 | Concept Study or Feasibility | Primarily Stochastic | 3 to 12 | 2 to 4 |
| Class 3 | 10 to 40 | Budget, Authorisation or Control | Mixed but Primarily Stochastic | 2 to 6 | 3 to 10 |
| Class 2 | 30 to 70 | Control or Bid/Tender | Primarily Deterministic | 1 to 3 | 5 to 20 |
| Class 1 | 50 to 100 | Check Estimate or Bid/Tender | Deterministic or Judgement | 1 | 10 to 100 |

**Table 4.1:** Classification of Cost Estimates (Turton *et al.*, 2008)

## 4.1 Estimation Methods of Capital Investment Cost

Total capital investment costs consist of land, fixed capital investment, offsite capital, allocated capital, working capital, start-up expenses, and other capital items (Green and Perry, 2008). Estimates of capital investment costs are usually classified in one of five types according to Green and Perry (2008):

1. Order-of-magnitude Estimate
2. Study Estimate
3. Preliminary Estimate
4. Definitive Estimate
5. Detailed Estimate

These estimate classifications are similar to those created by the AACE Recommended Practice No. 17R-97, shown in Table 4.1. This can be used to predict how accurate certain estimates will be. Class 1 estimates are between +6% and -4% accurate. By using this as a benchmark, in combination with the expected accuracy range for each estimate class, a high and low estimate range can be determined. For example, a class 4 estimate has an expected accuracy range of 3 to 12, relative to the best index of 1. Its lowest expected cost range will be between +18% and -12%, while its highest expected cost range will be between +72% and -48% of actual plant costs. It is important that this study comes as

| Capital Cost Type | Requirement |
|---|---|
| Site | Location and general description |
| Process Flow | Rough sketches |
| Equipment | Rough sizes and construction |
| Buildings and Structures | Rough sizes and construction |
| Utilities | Rough Quantities |
| Piping and Insulation | Preliminary flow sheets |
| Electrical | Rough motor list and sizes |
| Work-hours | Engineering and drafting |
| Project Scope | Product, capacity, location, utilities, and services |

**Table 4.2:** Requirements of a Factored Study Estimate (Green and Perry, 2008)

close as possible to actual plant costs.

A concept study or feasibility study is done in this project. To do this, capital investment estimates are required with regard to site, process flow, equipment, buildings, utilities, piping and insulation, electrical, and work-hours. Green and Perry (2008) give a description of the requirements with regard to these factors, specifically to a study estimate. These are displayed in Table 4.2.

The best practice in estimating equipment cost is to obtain a quote from a vendor of the required equipment. However, it is not always possible to obtain these quotes, especially when dealing with specialised equipment such as vacuum melting furnaces required for the melting of titanium. In these cases, estimates can be made from past cost estimates of similar equipment. Past studies very seldom deal with exactly what is required, and so must be adjusted to be relevant to the study. Equipment costs are adjusted to account for changes in capacity and time since the equipment was purchased.

### 4.1.1 Effect of Capacity on Investment Cost

In cases where the desired plant output capacity and the capacity of the obtained quote differ, the plant equipment cost can be adjusted by Equation 4.1.1 below.

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n \tag{4.1.1}$$

where:

A = Equipment Cost Attribute

C = Purchased Cost

n = Cost Exponent

a refers to equipment with the required attribute

b refers to equipment with the base attribute

The equipment cost attribute used most commonly is the capacity of the plant. The value for $n$ differs with equipment. In general when using this equation, the six-tenths rule is used. The rule explains that the differences in $n$ values for a plant usually cancel each other out and end up being about 0.6 for the entire plant (Turton *et al.*, 2008). The six-tenths rule accounts for the economy of scale in equipment costs, since larger equipment costs usually leads to lower equipment costs per unit of capacity.

### 4.1.2 Effect of Time on Investment Cost

The equipment cost data found may often be a few years old. To account for inflation since the time of the used cost estimate, cost indexes can be used in conjunction with Equation 4.1.2.

$$C_2 = C_1 \left(\frac{I_2}{I_1}\right) \tag{4.1.2}$$

where:

C = Purchased Cost

I = Cost Index

1 refers to base time when cost is known

2 refers to time when cost is desired

Cost indexes such as the Marshall and Swift Equipment Cost Index and the Chemical Engineering Plant Cost Index (CEPCI) are common indexes used in the industry. To use the equation, the current or desired time frame index is used and divided by the index at the time of available data, which is then multiplied by the available cost estimate. This accounts for the effect the time may have had on equipment costs. A collection of CEPCI values since 1995 are given in Table 4.3.

### 4.1.3 Accounting for Inflation

When a project will be installed at a future time, the cost estimation needs to account for inflation from the time of the estimation to the planned installation time. While the CEPCI values explained above deals with adjusting for inflation for past data, this section deals with adjusting of future values. An example for accounting for inflation in a project planned three years in advance is shown in Equation 4.1.3.

$$C_i = (1 + f_1)(1 + f_2)(1 + f_3)C_p \tag{4.1.3}$$

where:

$C_i$ = Inflated Cost

$f_1$ = Inflation Rate in the First Year

$f_2$ = Inflation Rate in the Second Year

$f_3$ = Inflation Rate in the Third Year

$C_p$ = Cost in a Base Year

| Year | CEPCI Value |
|---|---|
| 1995 | 381.1 |
| 1996 | 381.7 |
| 1997 | 386.5 |
| 1998 | 389.5 |
| 1999 | 390.6 |
| 2000 | 394.1 |
| 2001 | 394.3 |
| 2002 | 395.6 |
| 2003 | 402 |
| 2004 | 444.2 |
| 2005 | 468.2 |
| 2006 | 499.6 |
| 2007 | 525.4 |
| 2008 | 575.4 |
| 2009 | 521.9 |
| 2010 | 550.8 |
| 2011 | 585.7 |
| 2012 | 584.6 |
| 2013 | 567.3 |
| 2014 | 576.1 |
| 2015 | 556.8 |

**Table 4.3:** CEPCI Values from 1995 to 2015 (Magnehi, 2011; Chemical Engineering, 2016)

### 4.1.4 Estimating Total Plant Cost

Other than equipment costs, many other factors contribute toward the total cost of erecting a production plant. Once the six-tenths rule is used to account for capacity and Equation 4.1.2 is used to adjust the data to the desired time period, these additional cost estimates need to be performed. According to Turton *et al.* (2008), total plant costs can be divided into categories for direct project expenses, indirect project expenses, contingency and fees, and auxiliary facilities. These additional costs, including all their sub costs can be calculated by either the Lang Factor technique, the module costing technique, or by the bare module cost for equipment at base/non-base conditions (Turton *et al.*, 2008).

The simplest method of calculating total capital expenditure on a plant is by the Lang Factor technique. The method is used to determine the cost of an expansion to an existing plant. The cost is calculated by multiplying a Lang Factor (constant) with the total purchased equipment cost. This is shown in Equation 4.1.4.

$$C_{TM} = F_{Lang} \sum_{i=1}^{n} C_{p,i} \tag{4.1.4}$$

where:

$C_{TM}$ = Capital Cost (Total Module) of the Plant

$C_{p,i}$ = Purchased Cost for Major Equipment Units

n = Total Number of Individual Units

$F_{Lang}$ = The Lang Factor

The purchased cost used is for all major equipment units. Major equipment units are those which can be seen in the process flow diagrams. Lang factors which should be used are shown in Table 4.4. Lang Factors differ depending on the state of the matter which is processed in the plant. Lang Factors illustrate how greatly the total plant cost is affected by factors other than equipment cost, with equipment cost contributing less than a third of total plant costs in all cases. Lang factors for determining the fixed and total capital investment costs are given by Green and Perry (2008) and shown in Table 4.5. These differ from the values given by Turton *et al.* (2008).

| Type of Plant | Lang Factor |
|---|---|
| Fluid Processing Plant | 4.74 |
| Solid-Fluid Processing Plant | 3.63 |
| Solid Processing Plant | 3.10 |

**Table 4.4:** Lang Factors for Types of Processing Plants (Turton *et al.*, 2008)

| Type of Plant | Fixed Capital Investment | Total Capital Investment |
|---|---|---|
| Solid Processing Plant | 4.0 | 4.7 |
| Solid-Fluid Processing Plant | 4.3 | 5.0 |
| Fluid Processing Plant | 5.0 | 6.0 |

**Table 4.5:** Lang Factors for Fixed Capital and Total Capital Investments (Green and Perry, 2008)

Ruhmer (1987) did a breakdown of the Lang Factor method, applicable to South African metallurgical cost analysis. In addition to this, the given Lang Factors are broken down, showing the detailed influence of each factor on the cost estimation. These values are shown in Table 4.6.

| Type of Plant | Solids Handling | Hydrometallurgical | Chemical |
|---|---|---|---|
| Equipment | 1.0 | 1.0 | 1.0 |
| Erection of items | 0.11 | 0.17 | 0.11 |
| Structural and Buildings | 0.26 | 0.24 | 0.21 |
| Civils | 0.17 | 0.27 | 0.38 |
| Piping and Ducting | 0.14 | 0.35 | 0.59 |
| Electrical | 0.26 | 0.25 | 0.35 |
| Instruments | 0.1 | 0.2 | 0.27 |
| Installed Plant | 2.04 | 2.48 | 2.91 |
| GST (13%) | | | |
| Site Preparation (5%) | | | |
| Construction Management (15%) | | | |
| Contingency (15%) | 3.2 | 3.89 | 4.57 |

**Table 4.6:** Lang Factors Breakdown for South African Metallurgical Applications (Ruhmer, 1987)

This method is suitable for a study estimate. More thorough methods exist, but these are only used in preliminary, definitive and detailed estimates and are therefore not applicable to this study.

## 4.2 Manufacturing Cost Estimation Methods

Manufacturing costs can be broken down into direct costs, fixed costs and general expenses. Direct manufacturing costs are operating expenses which vary with the production rate, while fixed costs remain unaffected by changes in production rate. General expenses are other costs which are necessary to carry out business functions. They are associated with management level and administration activities and, similar to fixed costs, are not directly related to the manufacturing process. Turton *et al.* (2008) uses formulae to estimate manufacturing costs using multiplication factors. Equation 4.2.1 shows the base formula used to calculate total manufacturing costs. As can be seen, the total cost of manufacture is the sum of the above mentioned direct and fixed manufacturing costs, and general expenses.

$$COM = DMC + FMC + GE \tag{4.2.1}$$

where:

COM = Cost of Manufacture

DMC = Direct Manufacturing Costs

FMC = Fixed Manufacturing Costs

GE = General Expenses

To use this formula, the following values are required:

- Fixed Capital Investment (FCI): ($C_{TM}$ or $C_{GR}$)
- Cost of Operating Labour ($C_{OL}$)
- Cost of Utilities ($C_{UT}$)
- Cost of Waste Treatment ($C_{WT}$)
- Cost of Raw Materials ($C_{RM}$)

If these values are known, all other manufacturing costs can be estimated from multiplication factors given by Turton *et al.* (2008).

### 4.2.1 Direct Manufacturing Expenses

Direct manufacturing costs include raw materials, waste treatment, utilities, operating labour, supervisory labour, clerical labour, maintenance and repairs, operating supplies, laboratory charges, patents, and royalties.

The raw material expense is the most obvious direct expense. This is the amount one pays for the company's feedstock material. Data for raw materials can be estimated from the processes' material balance equation. The amount of raw material acquired needs to account for losses in production, such as melt losses in the case of titanium melting. Normally, the raw material expense is the largest manufacturing expense. This may be false in the case of titanium recycling, as the feedstock material can be bought at low cost, and the process of melting induces large utility costs and expensive crucibles are used.

Utilities also fall under this section, which include costs for steam, electricity, cooling water, fuel, compressed air, inert gas, instrument air, process water, boiler feed water, and refrigeration. These costs can also be calculated from energy and mass balances for processes. Plant utility supervisors or plant accountants may also be able to provide data on utility usage.

Operating labour refers to the cost of personnel operating the plant. To estimate labour requirements, a table of shift, weekend and vacation coverage needs to be prepared. Batch operations require a labour table, containing the tasks and number of operators required per task. Operator rates can be obtained from a union contract or a company labour relation supervisor. Supervision costs can be estimated at 15% to 30% of operating labour (Green and Perry, 2008).

Maintenance cost is also included under direct costs. Maintenance consists of materials and labour components, which contribute approximately 60% and 40% respectively. A value of between 6% and 10% of fixed capital is a good assumption for maintenance (Green and Perry, 2008). Payroll charges include factors such as the workers' compensation, social security premiums, unemployment taxes, paid vacations, holidays and health, and dental insurance. It is calculated at about 30% to 40% of operator labour plus supervision expenses according to Green and Perry (2008). Environmental control or waste treatment expenses are necessary to account for disposal and treatment of manufacturing wastes in an environmentally friendly fashion. The disposal of lubrication fluid from washed swarf is an example of waste from the process which needs to be treated and disposed of in a manner that doesn't have a negative effect on the environment.

Additional miscellaneous direct expenses include those involved with operating supplies, clothing and laundry, laboratory expenses, royalties, and patents. According to Green and Perry (2008), operating supplies is estimated at 5% to 7% of operating labour. Clothing and laundry, and laboratory expenses are 10% to 15% and 10% to 20% of operating labour respectively, while royalties and patents are calculated at 1% to 5% of sales. Equation 4.2.2 is used to calculate the total direct manufacturing costs, which is given by Turton *et al.* (2008).

$$DMC = C_{RM} + C_{WT} + C_{UT} + 1.33C_{OL} + 0.03COM + 0.069FCI \tag{4.2.2}$$

The values of the factors in Equation 4.2.2 are determined by using the midpoint of range values given in Table 4.7 and calculating their sum. Similar to Green and Perry (2008), Turton *et al.* (2008) estimates the majority of direct expenses using only fixed capital investment, operating labour, utilities, waste treatment and raw materials costs as required input.

| Direct Manufacturing Cost | Typical Range |
|---|---|
| Raw Materials | $C_{RM}$ |
| Waste Treatment | $C_{WT}$ |
| Utilities | $C_{UT}$ |
| Operating Labour | $C_{OL}$ |
| Direct Supervisory and Clerical Labour | (0.1-0.25)$C_{OL}$ |
| Maintenance and Repairs | (0.02-0.1)FCI |
| Operating Supplies | (0.1-0.2)(Maintenance and Repairs) |
| Laboratory Charges | (0.1-0.2)$C_{OL}$ |
| Patents and Royalties | (0-0.06)COM |

**Table 4.7:** Multiplication Factors for Estimating Direct Manufacturing Costs (Turton *et al.*, 2008)

### 4.2.2 Fixed Manufacturing Expenses

Fixed manufacturing costs, consists of depreciation, local taxes and insurance, and plant overhead costs. Depreciation allows a company to account for the value lost because of the age of assets. Plant indirect expenses include local taxes and insurance. Green and Perry (2008) estimates that plant indirect expenses can be calculated by using 2% to 4% of fixed capital investment. Plant overhead costs include payroll and accounting services, fire protection, safety services, medical services, cafeteria and recreational facilities, payroll overhead, and employee benefits.

| Fixed Manufacturing Cost | Typical Range |
|---|---|
| Depreciation | 0.1FCI |
| Local Taxes and Insurance | (0.014-0.05)FCI |
| Plant Overhead Costs | (0.5-0.7)($C_{OL}$ + Direct Supervisory and Clerical Labour + Maintenance and Repairs) |

**Table 4.8:** Multiplication Factors for Estimating Fixed Manufacturing Costs (Turton *et al.*, 2008)

Similar to Equation 4.2.2, Equation 4.2.3 uses the midpoints of the ranges given in Table 4.8 to determine its multiplication factors.

$$FMC = 0.708C_{OL} + 0.068FCI + depreciation \tag{4.2.3}$$

### 4.2.3 General Expenses

The final factor in manufacturing cost calculations is general expenses. This includes costs associated with maintaining sales offices, staff engineering departments, research and development, and administration offices. Green and Perry (2008) estimates general expenses to be about 6% to 15% of the product's annual revenue. Equation 4.2.4 is used to calculate general expenses, using factor averages from Table 4.9.

$$GE = 0.177C_{OL} + 0.009FCI + 0.16COM \tag{4.2.4}$$

| General Manufacturing Cost | Typical Range |
|---|---|
| Administration | 0.15($C_{OL}$ + Direct Supervisory and Clerical Labour + Maintenance and Repairs) |
| Distribution and Selling Costs | (0.02-0.2)COM |
| Research and Development | 0.05COM |

**Table 4.9:** Multiplication factors for General Manufacturing Costs (Turton *et al.*, 2008)

## 4.3 Economic Analysis

Many factors influence the profitability of a plant. This includes depreciation, the time value of money, taxes, inflation and exchange rates. In this section these factors are discussed and the formulae to incorporate these factors into a financial model are given.

### 4.3.1 Depreciation

Depreciation is an allowance for the decrease of value of property over time. Value decreases because of deterioration, wear and tear, and normal obsolescence over a period of time. Depreciation is intended to provide a method for the recovery of value of the asset as all assets have a finite life.

The depreciation period begins once the product is put into service and ends once the cost of the asset has been fully recovered or it is retired from service. This provides a value for which the assets can be salvaged after use or if the plant is closed. According to Green and Perry (2008), depreciation is inherently linked to taxes. This is because many tax laws incorporate depreciation as a core component. The rate and method of depreciation is determined by the appropriate tax authority, the South African Revenue Service (SARS) in the case of South Africa.

What can and cannot be depreciated should also be discussed. Fixed capital includes all the values explained in the estimation of capital investment costs. Of this, only land cannot be depreciated. Working capital is the amount of capital required to start up the plant and finance the company for the first few years. Working capital is fully recoverable and therefore, not depreciable. Working capital can be estimated at about 15% to 20% of fixed capital investment. Terms associated with depreciation include the following:

- Fixed Capital Investment, $FCI_L$ - The fixed capital investment minus the value for land, which is not depreciable.
- Salvage Value, S - The value of $FCI_L$ at the end of the plant's life.
- Life of Equipment, n - Represents the time allowed for depreciation by the tax authority, not the actual operating life of equipment.

Total capital for depreciation is the difference between fixed capital investment and salvage value as shown in Equation 4.3.1 below.

$$D = FCI_L - S \tag{4.3.1}$$

where:

D = Total Capital for Depreciation

Yearly depreciation is when the amount of depreciation varies from year to year. It is denoted by $d_k$, for the $k$th year. The book value of an asset is the amount of depreciable capital that has not been depreciated. The calculation for book value is shown in Equation 4.3.2.

$$BV_k = FCI_L - \sum_{1}^{k} d_j \tag{4.3.2}$$

where:

$BV_k$ = Book Value

There are three methods for calculating depreciation, namely the Straight-Line, Double-Declining-Balance and Sum-of-the-Years-Digits method. The Straight-Line method (SL) has an equal amount of depreciation each year over the depreciation period.

$$d_k^{SL} = \frac{[FCI_L - S]}{n} \tag{4.3.3}$$

In Sum-of-the-Years-Digits-Depreciation (SOYD), the yearly depreciation is set as a declining fraction, which is calculated by Equation 4.3.4.

$$d_k^{SOYD} = \frac{[n+1-k][FCI_L - S]}{\frac{n}{2}[n+1]} \tag{4.3.4}$$

Finally, Double-Declining-Balance-Depreciation (DDB) uses a constant fraction of the book value, $BV_{k-1}$. Equation 4.3.5 is used to calculate this.

$$d_k^{DDB} = \frac{2}{n}\left[FCI_L - \sum_{j=0}^{j=k-1} d_j\right] \tag{4.3.5}$$

### 4.3.2 Time Value of Money

This section explains the effect of time on the value of maoney, with equations sourced from Green and Perry (2008). In business, money is loaned or borrowed. When money is borrowed, it needs to be returned with interest to compensate the loaner for the money. The amount of the loan is called the principle value (P), also referred to as present value. Once a time period has passed, the value of loaned money becomes greater. The future amount (F) or future value is the value of the money at a period after the time the money was loaned. There are two types of interest used when the future value of an investment is calculated, namely simple and compound interest. Simple interest is rarely used today. The amount of interest paid is based purely on the initial investment. The equation for the calculation of simple interest is shown in Equation 4.3.6.

$$F_n = P(1 + i_s n) \tag{4.3.6}$$

where:

P = Present Value

F = Future Value

$i_s$ = Simple Interest Rate

$n$ = Number of Years

If the interest earned is reinvested, instead of being set aside, it is known as compound interest. The equation to determine the future value with a compounding interest rate is given by Equation 4.3.7.

$$F_n = P(1 + i)^n \tag{4.3.7}$$

To determine the present value, for use when one wants to calculate the amount which needs to be invested at present to reach a certain future value after a set amount of years, Equation 4.3.8 is used.

$$P = \frac{F_n}{(1 + i)^n} \tag{4.3.8}$$

In some cases when the interest rate is not given as compounded per year, the effective interest rate ($i_{eff}$) can be calculated. This converts interest rate, given as compounded monthly, bi-annually, quarterly or otherwise to an effective annual interest rate. Equation 4.3.9 is used to convert this.

$$i_{eff} = \left(1 + \frac{i_{nom}}{m}\right)^m - 1 \tag{4.3.9}$$

where:

$i_{eff}$ = Effective Annual Interest Rate

$i_{nom}$ = Given Nominal Interest Rate

$m$ = Number of Compounding Periods per Year

To cover for the initial capital investment costs, a loan typically needs to be taken out and repaid in monthly instalments. Equation 4.3.10 is used to determine the monthly loan payment amount.

$$\mathrm{A} = \mathrm{P}\frac{r(1 + r)^n}{(1 + r)^n - 1} \tag{4.3.10}$$

where:

A = Payment Amount per Period

P = Initial Loan Amount

r = Interest Rate per Period

n = Number of Payments or Periods

### 4.3.3 Taxation

Depreciation and income influence the amount of income tax which should be paid. Turton *et al.* (2008) provides equations for calculating income tax, after-tax (net) profit and after-tax cash flow in Equations 4.3.11 to 4.3.13.

$$\text{Income Tax} = (R - COM_d - d)(t) \tag{4.3.11}$$

where:

$COM_d$ = Expenses (Manufacturing Costs + Depreciation)

d = Depreciation

t = Tax Rate

R = Revenue from Sales

$$\text{Net Profit} = (R - COM_d - d)(1 - t) \tag{4.3.12}$$

$$\text{After-Tax Cash Flow} = (R - COM_d - d)(1 - t) + d \tag{4.3.13}$$

### 4.3.4 Cumulative Cash Position Plot

The cumulative cash position or cash flow diagram gives a running total of the cumulative cash in the company up to that point in time. Expenditures and revenue are plotted as a function of time. Discounting factors are added, which are used to account for the time value of money. It uses an equation similar to Equation 4.3.8. Projected future profits are discounted using these rates and the discounted NPV can thus be calculated. This can then be used to compare alternative projects.

## 4.4 Profitability Analysis

Profitability can be measured according to time, cash or interest rate. For each of these measures, profitability can be assessed using discounted or non-discounted techniques. The latter will not be discussed, as it does not take into account the time value of money and is rarely used to evaluate large projects (Turton *et al.*, 2008). The time criterion used is the discounted payback period (DPBP). This is a measure of the amount of time it takes to pay back the fixed capital investment ($FCI_L$), with all cash flows discounted back to time zero. The most desirable project will be the one with the shortest payback period. Green and Perry (2008) use the term Payout Period Plus Interest (POP + I) to describe the same calculation. Equation 4.4.1 shows the calculation.

$$\text{POP} + \text{I} = \frac{\text{Depreciable Fixed Capital Investment}}{\text{After-Tax Cash Flow}} \tag{4.4.1}$$

The cash criterion used is the Discounted Cumulative Cash Position, also known as Net Present Value (NPV) or Net Present Worth (NPW). The NPV is the cash position at the end of the project period and is shown in Equation 4.4.2.

$$\text{NPV} = \text{PV of all Cash Inflows} - \text{PV of all Investment Items} \tag{4.4.2}$$

The Present Value Ratio (PVR) can be a useful measure of profitability when comparing projects. It shows whether a project will be profitable, with values greater than 1 indicating a profitable project and those less than 1 indicating unprofitable projects.

$$\mathrm{PVR} = \frac{\text{PV of All Positive Cash Flows}}{\text{PV of All Negative Cash Flows}} \tag{4.4.3}$$

To evaluate profitability using interest rates, the Discounted Cash Flow Rate of Return (DCFROR) is used. This gives an interest rate for the project for which the NPV at the end of the period will be zero. It thus shows the greatest after-tax interest rate at which a project will break even.

## 4.5 Accounting for Uncertainty

The methods explained above are deterministic in nature, as they provide a certain answer for the profitability of a project in the form of a NPV, DPBP or DCFROR, which is assumed to be known with certainty. In reality input values vary considerably from the time a project is implemented to the end of the analysis period. As shown is Table 4.10, the initial estimates may value considerably over a 10 year period. This variation contributes towards the accuracy of cost estimates shown in Table 4.1.

| Factor in Profitability Analysis | Probable Variation over 10 Year Period [%] |
|---|---|
| Cost of Fixed Capital Investment | -10 to +25 |
| Construction Time | -5 to + 50 |
| Start-up Costs and Time | -10 to +100 |
| Sales Volume | -50 to +150 |
| Price of Product | -50 to +20 |
| Plant Replacement and Maintenance Costs | -10 to +100 |
| Income Tax Rate | -5 to +15 |
| Inflation Rate | -10 to +100 |
| Interest Rate | -50 to +50 |
| Working Capital | -20 to +50 |
| Raw Material Availability and Price | -25 to +50 |
| Salvage Value | -100 to +10 |
| Profit | -100 to +10 |

**Table 4.10:** Expected Cost Variation Over a Ten Year Analysis Period (Turton *et al.*, 2008)

Scenario Analysis, Sensitivity Analysis and Monte-Carlo Simulation can be done to investigate and account for uncertainty in a cost model (Turton *et al.*, 2008). The @Risk tool is used to introduce probability into the model in this investigation.

### 4.5.1 Scenario Analysis

In Scenario Analysis, the best, worst and base-cases are evaluated. The bottom ranges for all estimate values are used to investigate the worst-case scenario or most pessimistic option. The base-case uses the base values, similar to those in a normal deterministic analysis.

Similar to the worst-case scenario, the best-case scenario uses the top range values to determine the most optimistic option. In a case where three values are chosen as inputs for a model, namely revenue, cost of manufacturing and capital investment, the best and worst-cases will only have a one in twenty-seven chance of occurring. This is because for each of the three values, there are three options (low, high and base), which means there are 27 possible combinations. While it is useful to analyse the best and worst-cases, the probability that these cases will occur is very low and often not realistic. This is the negative aspect of scenario analysis. To improve on this method, output values should be weighted, based on their probability of occurrence. This is the basic idea behind Monte-Carlo Simulation.

### 4.5.2 Sensitivity Analysis

Sensitivity Analysis allows one to investigate the impact a variable has on the output measure. In this case the output measure is one of the three measures of profitability. If NPV is chosen as the profitability measure, the sensitivity of a variable ($x_1$) can be determined by Equation 4.5.1 if the sensitivity is affected by variables $x_1$, $x_2$, ..., $x_n$.

$$S_1 = \left[\frac{\delta(\text{NPV})}{\delta x_1}\right]_{x_2,x_3,\ldots,x_n} \tag{4.5.1}$$

In this equation, the partial derivative is taken with respect to $x_1$, and holds all other parameters constant at mean value. $S_1$ is known as a sensitivity coefficient. Obtaining the partial derivative can often be too complicated and can be estimated by Equation 4.5.2.

$$S_1 \approx \left[\frac{\Delta(\text{NPV})}{\Delta x_1}\right]_{x_2,x_3,\ldots,x_n} \tag{4.5.2}$$

Once sensitivity coefficients have been calculated, the influence of changes in parameter values on the NPV can be easily be analysed with the use of Equation 4.5.3. This allows one to see how big an effect certain input parameters have on output values and create hypothetical "what-if" scenarios.

$$\Delta\text{NPV} = S_1\Delta x_1 + S_2\Delta x_2 + \ldots + S_n\Delta x_n \tag{4.5.3}$$

### 4.5.3 Monte-Carlo Simulation (M-C)

The steps to conduct an Monte-Carlo Simulation is given in Turton *et al.* (2008) and is as follows:

1. Identify and quantify all parameters which involves uncertainty
2. Assign probability distributions to these parameters
3. Assign a random number for each parameter
4. Assign a value to the parameter, by using the random number and its probability distribution
5. Estimate the value of NPV once this process has been completed for all parameters

6. Repeat steps 3, 4 and 5 many times over (1000 times or more)
7. Create a histogram and cumulative probability curve for the results of Step 6
8. Analyse the profitability of the project from the data created in Step 7

The @Risk tool will be used to conduct a M-C Simulation in this project. The tool allows one to fit a range of distributions over a dataset, or create your own by giving certain estimates, such as minimum, maximum and most likely values. Many types of distributions exist, the simplest are uniform and triangular distributions. Uniform distributions allow a parameter to take a value between $a$ and $b$, with equal probability. A triangular distribution requires a minimum ($a$), maximum ($c$) and most likely ($b$) value. This distribution allows a greater chance that values close to the most likely value will be selected. The probability function is given to by Equations 4.5.4 and 4.5.5, depending on the value of $x$.

$$p(x) = \frac{2(x-a)}{(c-a)(b-a)} \text{ for } x \leq b \tag{4.5.4}$$

$$p(x) = \frac{2(c-x)}{(c-a)(c-b)} \text{ for } x > b \tag{4.5.5}$$

Other types of distributions, such as normal, lognormal and trapezoidal can easily be used as well. @Risk allows the user to create these distributions, so that they most accurately represent realistic possible values. The resulting M-C Simulation allows one to determine the probability of a project being profitable quantitatively. This can then be used to make more informed decisions, taking into account all the risk involved in the project and their likelihood of occurrence.

# Chapter 5

# Research Methodology

The methodology followed in this study is depicted in Figure 5.1. A divergent-covergent approach was used, which is illustrated by the grey diamond shape in the background of the figure. This represents the way in which the scope of the study broadened or diverged from the initial problem statement as more recycling methods and cost modelling techniques were found in reviewing literature.

All these alternatives were evaluated in the feasibility study, which resulted in the converging shape as infeasible alternatives were eliminated. This trend continued, until only the best alternatives remained. The first phase consists of the initial problem statement, project aim, research objectives and scope, which are defined and described in Chapter 1. The analysis stage follows this, which entails the literature reviews on titanium, recycling thereof, and cost modelling, done in Chapters 2 to 4. This gives a deeper understanding of the problem and allows gaps in the literature to be identified. Using this knowledge, phase 2 is initiated. Phase 2 entails a background case study on scrap recycling and the development of the feasibility model.

A background study was done to analyse a state-of-the-art local recycling process at Hansens Engineering. This provided valuable insights into new machine scrap recycling and data with regards to labour, waste disposal, and equipment costs. These are used as inputs for the feasibility study and cost model.

The feasibility study requires additional cost data to be added, in addition to Lang Factors and benchmark components. Cost data and Lang Factors are identified through the initial literature review. Benchmark components are obtained from past projects at Stellenbosch University. A feasibility cost model is developed, which allows the break-even analysis to be conducted. With use of this and general background information on titanium recycling processes, the feasibility framework is compiled. Benchmark components are used to provide some real world context. This shows the break-even analysis in terms of a number of components, needed to be produced, instead of a break-even scrap weight.

While many outputs are obtained from the feasibility study, it serves the additional purpose of identifying the most suitable alternative for titanium recycling in the current state. This alternative is then simulated in phase 3 by use of the Monte-Carlo Simulation. Uncertainty is introduced into the model by doing so, and one can determine the probability of the project being financially successful.

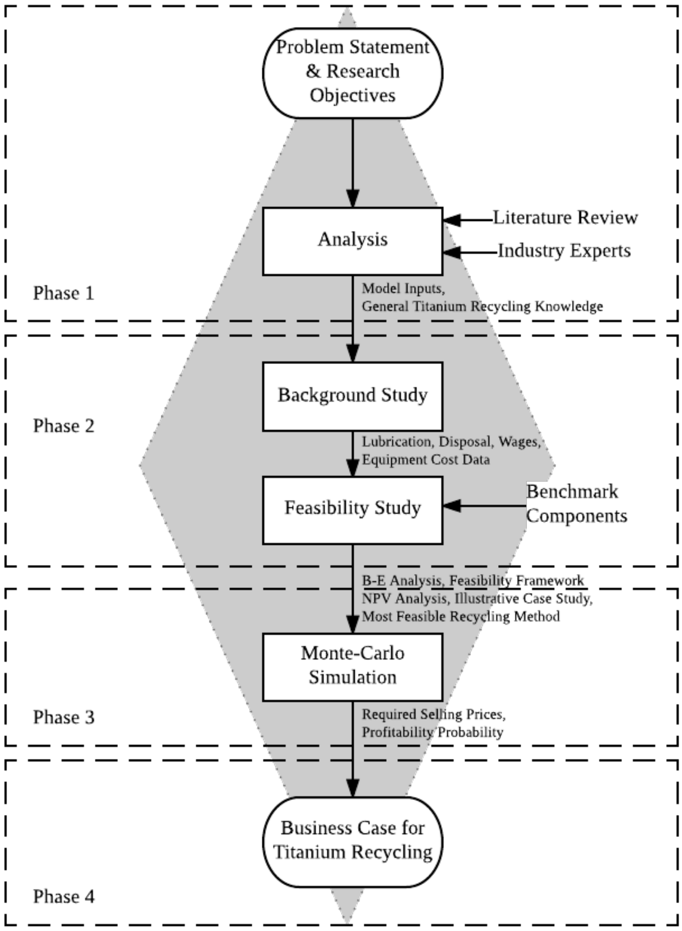


**Figure 5.1:** Methodology Followed in this Research Study

## 5.1 Background Study

In this section the background study on state-of-the-art new scrap recycling is explained. A background of Hansens' production process is given and the methodology followed by the case study is explained. The three waste-to-resource strategies, namely the conventional machine setup, retrofitted minimum quantity lubrication (MQL) combined with a central briquetting system, and the new prototype machine with built-in briquetting system and no lubrication, are introduced as well.

The facility at Hansens Engineering produces aluminium parts for use in the automotive industry. Machining of these parts creates a considerable amount of scrap, because of the high volumes they produce, the in-house recycling process of which is analysed. The general metal material cycle is shown in Figure 3.1. Hansens falls under the "Product Manufacture" step, highlighted in grey. Out of this process flows products, new scrap and residues. In this section, as is done by the engineers at Hansens, this new scrap is seen as a valuable product on its own and not a waste product. Residues arise from this operation which entails everything which is not recycled and directly disposed of. These can be minimised by implementing resource efficient manufacturing strategies, such as MQL and automatic briquetting systems, ensuring a larger amount of swarf (new scrap) can be recovered which has a greater economic value. This is a prime example of waste-to-resource processes, where swarf is used to produce a product of value, while simultaneously producing the machined component. Primarily, financial resources are compared in this background study, with discussions of the implications on environmental and human resources. The results of this background study are included in Chapter 6.

Lubrication and swarf processing systems are assessed as waste-to-resource strategies. MQL is a lubrication technique which implements very small amounts of lubrication fluid as explained in Section 3.3. This results in a near dry manufacturing environment. Hansens Engineering provides the ideal scenario to assess the implications of different waste-to-resource strategies, as they have implemented MQL and briquetting systems into their manufacturing processes, but still have conventional flood lubrication systems installed in older processes. Swarf is sold in briquette and loose form, which is another strategy that can be assessed. This creates a platform where in-house recycling for different scenarios can be compared.

While the waste-to-resource strategies that have been implemented in their older and current machines operate at a very high efficiency and result in very little wastage, the company continues to improve. Current projects include a prototype machine with built-in swarf briquetting system, essentially producing two sellable products simultaneously.

The research methodology followed is seen in Figure 5.2. A basic understanding of strategies affecting the quality of swarf, with regard to lubrication and packing density, is gained of MQL and briquetting technologies, is gained in the literature study. These waste handling strategies were then seen in action by conducting a background study at Hansens Engineering. This involves comparing traditional strategies with current, more efficient, waste-to-resource strategies and then a possible near-future improved process. These strategies are implemented on three different machine setups. They are then evaluated and compared in terms of capital investment costs, scrap value creation, lubrication costs, and environmental impact.

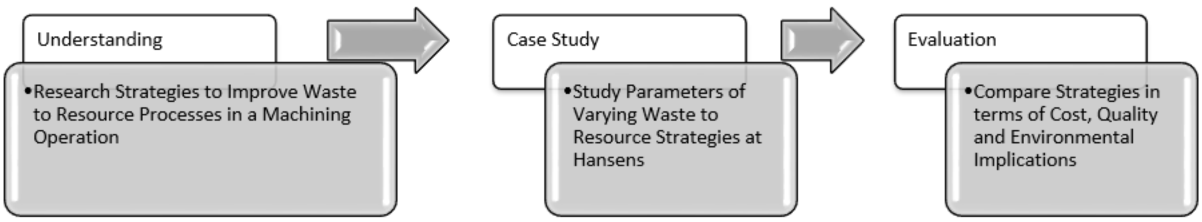


**Figure 5.2:** Methodology Followed in Background Study

Three cases are evaluated, each with differing waste management strategies. These strategies are:

- Conventional Machine Setup (Daewoo 2)

- Retrofitting MQL lubrication on machine with centralised briquetting system (Turning Cell 3)
- New prototype machine design with built-in briquetting system

All three machine setups are analysed assuming they are producing product V30-A02 (Figure 5.3), which is used in shock damper components for the automotive industry. The component volume and blank volume were calculated from CAD models. The percentage swarf produced by each part could then be calculated by subtracting the two. These values are shown in Table 5.1. The density of aluminium alloy ENAW 6082-T6 is 2.7 g/cm$^3$, and by utilising this, the weight of swarf per part V30-A02, can be calculated.

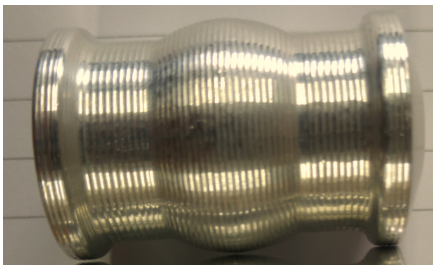

**Figure 5.3:** Part V30-A02

| Description | Volume (mm$^3$) |
|---|---|
| Blank | 19 957.61 |
| Component | 13 990.28 |
| Swarf Per Part | 5 967.33 |

**Table 5.1:** Volumes Associated with Producing Part V30-A02

### 5.1.1 Conventional Machine Setup

The conventional machine setup analysed is the Daewoo 2 setup, an operation with a profiling, drilling, chamfering and parting operation. In the conventional machine setup, lubrication is applied to the part and tool in the form of flood cooling. Once the machining operations are completed, wet swarf is produced as seen in Figure 5.4.

This wet swarf is sold to other companies, where it has to undergo a degreasing operation before it can be melted. In the past, oily swarf was added to the melting process without any cleaning operation, but the smoke resulting from the burn would have adverse effects on the factory workers (Schlesinger, 2013). Although called wet swarf, it has a small amount of lubrication on it. A system is implemented in the machine which removes the swarf at an incline, causing the majority of the lubrication fluid to stay in circulation in the setup. This results in relatively dry swarf, but not dry enough to compress to briquettes. A drying step thus needs to be implemented if one has the desire to process the wet swarf further in-house, which incurs additional process time and thus a slower throughput. There is a possibility that pockets of lubrication fluid can form in the compressed briquette if compressed when wet, which may combust when introduced

**Figure 5.4:** Wet Swarf Produced from Flood Lubricated Operation

into a smelting operation. This additional required process step is reflected in the buying price of loose wet swarf.

Lubrication fluid is reused in the operation, but needs to be disposed of after a given period and requires some upkeep. On a weekly basis the concentration of lubrication fluid is tested by a reflectometer. A lab analysis is done on a monthly basis to check the concentration and pH levels, din corrosion, and percentage tramp oil. These services are provided at no extra cost to Hansens. Once a year, flood coolant is treated with acticide and system cleaner.

### 5.1.2 Retrofitting MQL and Briquetting System

In the second setup analysed, waste-to-resource strategies were retrofitted to an existing machine setup. MQL and briquetting technologies were added to a turning cell to increase the value and decrease the processing requirements of the produced scrap.

Turning cell 3 has 5 machines. The process for each is similar, even though the parts they produce are marginally different. A blank is fed into the machine by 32mm bar with a 13mm centre hole, and clamped with a hydraulic draw. The blank starts to rotate and a cutting tool faces and profiles to part. Shortly after this process, a drill creates the centre hole. A part catcher substitutes the position of the drill and a parting tool separates the part from the remainder of the bar. The part drops onto the part catcher once separated, where a Motoman robot grabs it and places it on a pin. The part goes through an air gauge inspection to verify the dimensions of the centre hole and is fed into a box for electronic visual inspection thereafter. The part is sent down a bottom shoot if either of these inspections fail. If it passes both inspections, a back chamfer is added. The part undergoes further downstream washing operations to ensure cleanliness to finalise the product. This turning cell was retrofitted with a MQL setup. An image of the MQL setup on a turning machine is seen in Figure 5.5. The three lubrication feed pipes can be seen entering the machine, one for each contact point in the operation (profiling, drilling and parting). As seen in Figure 5.6, a ventilation system is installed in the machine cell as well. This is used to minimise the effect of mist created by the MQL setup and minimise health risks.

Implementing MQL is thus effective in creating a more resource efficient process chain in three ways. Firstly, with the reduced cost of purchasing lubrication fluid, as the volume required is so little, secondly because there is no disposal cost required for cutting fluid and finally, because it removes the requirement for further processing of scrap before it can

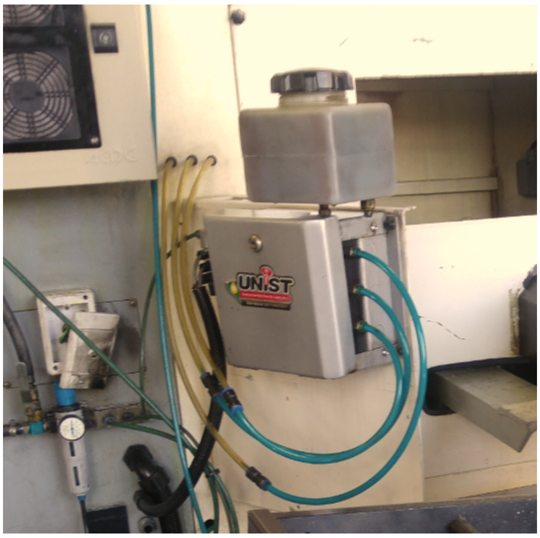


**Figure 5.5:** MQL System Implemented in Turning Cell 3

**Figure 5.6:** Ventilation System Installed on Machines in Machine Cell 3

be briquetted. The loose swarf is collected under the machine and periodically moved by hand to a central briquetting machine, which is used to briquette the entire machine cell's scrap. The briquetting machine is shown in Figure 5.7 without the top shredder. The shredder reduces the size of the machine swarf, so they can be compacted more tightly.

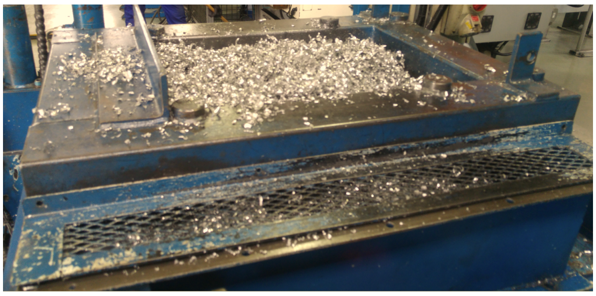

**Figure 5.7:** Loose Scrap Fed into Briquetting Machine

The resulting compacts can be seen in Figure 5.8. They are about 5cm in diameter and vary in length. This is fairly small, with the standard diameters in industry being between 12 cm and 50 cm (Schlesinger, 2013). The collected briquettes are shown in Figure 5.9. These briquettes are weighed in real time and the weight of the batch is displayed on the wall next to the briquetting machine.

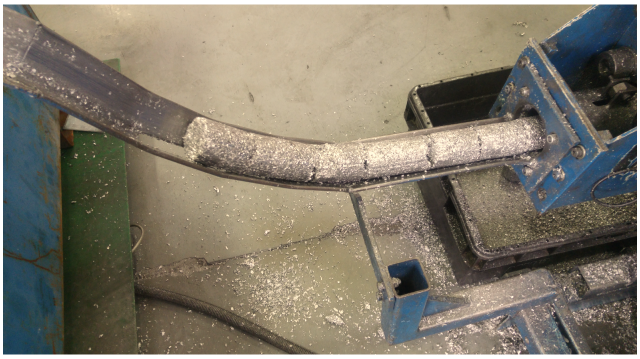

**Figure 5.8:** Aluminium Briquettes Produced

**Figure 5.9:** Collected Scrap Briquettes

Implementing this briquetting system results in a 70% increase in swarf value. Retrofitting these systems onto an existing machine does bring undeniable benefit with regards to the value gained from the produced waste, but can be an expensive exercise with regard to initial capital investment.

### 5.1.3 Built-in Waste-to-Resource System

The current state-of-the-art project being developed at Hansens involves a prototype machine which has a built-in system for shredding and briquetting machine swarf. Once implemented, these machines will be capable of producing a significantly larger amount of briquetted swarf, because of the reduced cycle time of the machine. Since the briquetting system is implemented in the machine itself, there is no need to transport loose swarf to a centralised position as is currently done. This will result in greater ease with regard to the handling of swarf and possibly reduce losses during the transportation thereof, moving ever closer to a 100% efficient material cycle.

While there is an MQL system installed on the prototype machine, the engineers at Granroth are looking to implement dry machining in the fully functional models. With reduced cycle time, resulting in increased scrap production, reduced scrap handling, because of the built-in briquetter, and no lubrication costs, these machines will have reduced process residues to a minute amount. A further benefit is that the prototype machine will be available at a cost similar to that of the machines in turning cell 3.

## 5.2 Feasibility Study

In order to conduct the feasibility study, the methods explained in Chapter 4 are used. The feasibility study serves as a measure to filter out recycling alternatives which are clearly infeasible at present. Figure 5.10 illustrates a simplified version of the method by which the financial feasibility models are created. Each model receives input in the form of equipment costs, operating labour, cost of waste treatment, utility costs, raw material costs and additional process parameters. These are then used to calculate the fixed capital investment, fixed manufacturing costs, direct manufacturing costs and general expenses through the use of the Lang Factors identified in Chapter 4. Through these cost models, break-even analysis and scenario analysis are performed.

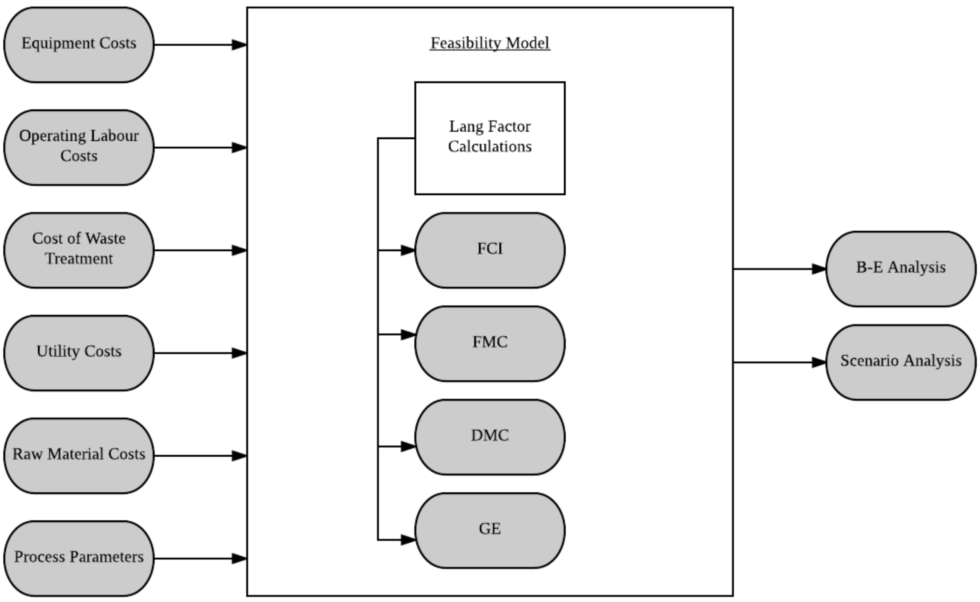


**Figure 5.10:** Simplified Operation of Economical Feasibility Models

An example of how Lang Factors are used to estimate capital investment costs is given as follows. The initial total equipment cost for the wash and briquette process is given as R2.95 million in Chapter 3. The multiplication factors in Table 4.6 show that the factor for the erection of items is 0.11. The estimated amount required for the erection of items, is then estimated to be R2 950 000 $\times$ 0.11 = R324 500. A similar process is followed when calculating all other parameters.

The first step in conducting the study is to normalise equipment data, adjusting for capacity and inflation using Equations 4.1.1 and 4.1.2. Large scale production methods are normalised to a capacity of 600 000 kg per annum, as this is the smallest principle producer of titanium melted products in the world, according to Roskill Information Services Ltd (2013). Once normalised, the total capital investment cost is calculated with the use of the Lang Factors given in Table 4.6, as they are specific to South Africa and the metallurgical industry. The manufacturing costs are calculated by use of the multiplication factors given in Table 4.7 to 4.9. Inputs for raw materials are estimated using the scrap values identified in Table 3.11, in Chapter 3. Waste treatment costs are estimated based on data obtained from Hansens. This describes the treatment required for cutting fluid, which needs to be disposed of in an environmentally-friendly manner. As the flood coolant used by Hansens is very similar to that used at Stellenbosch University's labs for the machining of titanium, it is relevant data.

Operating labour and utilities are estimated depending on the recycling process followed, as each setup differs with regard to electricity, water and labour requirements. Depreciation is added using a straight line method, shown by Equation 4.3.3. Yearly instalments required to cover a loan equal to the initial capital investment costs are calculated, adjusted for the time value of money. The monthly instalment to cover the costs of the load is given by Equation 4.3.10, which is multiplied by twelve to get the amount paid per annum. Corporate income tax is added, by use of Equation 4.3.11.

A cumulative cash flow diagram for each recycling route's base-case is created, which shows theoretical profitability of each project based on its NPV over a ten-year period, accounting for the time value of money using discounting factors. Scenario Analysis is done using best, worst and average-case scrap availability values, which gives an idea of the most optimistic and pessimistic possible outcomes of the project. An optimistic case is conducted, based on apparent consumption of imported titanium products. A pessimistic analysis is done, utilising the average scrap exports over the past ten years.

A break-even analysis is also done. By utilising Microsoft Excel's Goal Seek function, the throughput is varied to find the value for which the net present value of the project will be zero after ten years. In other words, it determines how much scrap needs to be processed, for each recycling method to have a positive net present value after 10 years. The decision-making feasibility framework is built on this, which is based on the preliminary framework built by Durr and Oosthuizen (2016), which can be seen in Appendix G.

Benchmark components are then used to provide some real-world contextualisation and validation in Section 5.2.10. The banana-brace, intercostal, wing riblet and knuckleduster are introduced in this section, with a breakdown of their applications and the amount of machine swarf they produce per part. As the break-even scrap amount for each recycling technology is known at this point, it can be used to determine the amount of parts needed to be produced to justify recycling through each technology. This provides manufacturers with a better idea of which recycling technology would be best to use.

To determine whether the recycling methods are feasible in the current state of the South African titanium industry, the required break-even throughput should be less than the maximum process capacity and have a positive NPV after ten years. If not, the recycling process will not be able to add enough value to scrap to justify all costs involved in setting up the process. The challenges in titanium recycling, identified in Chapter 3.3, are also taken into account when creating the feasibility framework.

The model requires some general inputs and process specific inputs. General inputs, referred to as "global inputs" in this section, include the amount of scrap available, scrap prices, utility prices, exchange rates and tax rates. Process specific inputs are concerned with the costs and throughputs of a specific recycling process. The full list of inputs for the feasibility model can be found in Appendix A.

### 5.2.1 Global Inputs

The amount of scrap available is a primary concern with regard to the feasibility of titanium recycling in South Africa's case. Low volumes of scrap may cause equipment to operate far below theoretical capacity. This may cause the payback period of initial investment costs to be very long, or make projects completely infeasible. Since the local titanium industry is unwilling to provide data on scrap production, estimates have to be made by the trade data available for titanium scrap metal. The simplest method of estimating the available scrap is to assume that all titanium scrap exported is available for recycling. Looking at scrap exports alone gives some idea of the available volume. Table 5.2 shows the exports of titanium scrap from South Africa since 2005. It can be seen that an average of about 55 kt scrap was exported in this time. The danger of this method is that some of the exported scrap may be surplus scrap, imported for use in the stainless steel industry. There is a possibility that this scrap is of low quality and should not be included as aerospace quality scrap.

| Year | Ti Scrap Export [kg] |
|---|---|
| 2005 | 28 069 |
| 2006 | 117 796 |
| 2007 | 25 163 |
| 2008 | 7 518 |
| 2009 | 939 |
| 2010 | 123 233 |
| 2011 | 83 704 |
| 2012 | 47 766 |
| 2013 | 3 207 |
| 2014 | 147 431 |
| 2015 | 25 325 |
| Average | 55 468.27 |

**Table 5.2:** Titanium Scrap Exported Since 2005 (DTI, 2016)

Another method of estimating the volume of available scrap is to look at the imports of articles of titanium, assuming that these are mill products such as billets, and subtract the export of articles of titanium, assuming that these are finished products, produced by Aerosud, Denel and other companies. The remainder would be a theoretical amount of scrap produced. Since South Africa has no industry producing titanium metal on a large commercial scale, all mill products need to be imported. The majority of titanium products made in South Africa are also exported, so the assumption could be relatively accurate. The advantage of this method is that there are more data points usable as they don't have massive outliers, which are frequent in old data for titanium scrap exports. The imports and exports of articles of titanium, with the estimated available scrap are

| Year | Mill Product Import [kg] | Titanium Articles Exports [kg] | Estimated Scrap [kg] |
|---|---|---|---|
| 2000 | 71 938 | 13 838 | 58 100 |
| 2001 | 338 380 | 39 143 | 299 237 |
| 2002 | 410 087 | 28 189 | 381 898 |
| 2003 | 88 064 | 60 632 | 27 432 |
| 2004 | 192 234 | 50 926 | 141 308 |
| 2005 | 118 046 | 33 291 | 84 755 |
| 2006 | 137 150 | 56 898 | 80 252 |
| 2007 | 186 234 | 67 345 | 118 889 |
| 2008 | 792 319 | 69 998 | 722 321 |
| 2009 | 89 169 | 46 807 | 42 362 |
| 2010 | 115 909 | 67 086 | 48 823 |
| 2011 | 111 262 | 55 730 | 55 532 |
| 2012 | 122 948 | 48 156 | 74 792 |
| 2013 | 269 989 | 41 259 | 228 730 |
| 2014 | 230 785 | 39 257 | 191 528 |
| 2015 | 496 976 | 53 503 | 443 473 |
| Average | 218 300.9 | 47 903.7 | 170 397.3 |

**Table 5.3:** Estimation of Titanium Scrap Available from Mill Products Trade (DTI, 2016)

shown in Table 5.3. The amount of imports are also always less than the exports and scrap rates are around 68% since 2000, which is a very conservative estimate for the titanium industry. The disadvantage is that large assumptions are made.

As a pessimistic rate, it will be estimated that 55 kt of titanium scrap is available to recycle per annum, based on the exported titanium scrap since 2005. Using the second method, it is estimated that about 170kt is available for recycling per annum. These values can then be used to determine conservative and optimistic estimates for equipment throughput capacity.

Interest on the initial loan is taken at 10.5%, which is the prime loan interest rate at the time of the study. A discounting rate of 7% is used to roughly account for inflation. Ten years depreciation is used for all the processes' equipment, as there were no relevant equipment life years in SARS's documents to that of titanium recycling or metal recycling in general. This allows for ease of calculations. The initial cost of scrap is taken as R16 per kilogram, as this is the amount Denel Aerostructures receive for their scrap. As shown in Table 3.9, the value of aerograde scrap is much higher than this, but as this study addresses the current South African titanium market, Denel's price is more applicable. Corporate income tax is taken at 28%, while the Rand-Dollar and Rand-Euro exchange rates are based on the average rates for 2016 up until the time of the study. This was taken to be roughly R13.89 per Dollar and R15.63 per Euro. Electricity costs are taken as the average rate for the industrial sector in South Africa in 2015, which is 63 cents per kWh, according to Eskom.

### 5.2.2 Scrap Washing and Briquetting Inputs

Inputs for titanium scrap processing were obtained from Granroth Engineering. This includes the equipment costs, which came to an estimated total of R2.95m, with a throughput of 50kg/hr. As these values are already normalised in terms of capacity and inflation, there is no need to adjust its cost. The values are shown in Chapter 3, in Table 3.2.

As discussed in Chapter 3.9, processing adds \$1.23 per pound to the market price of scrap, bringing the total selling price to \$6.82 per kilogram. Electricity costs are sourced mainly from product brochures, for products similar to the quotes obtained from Granroth. Estimated electricity use for drying, screening and conveying, was calculated using tables from Ruhmer (1987). The following data was used for electricity use per day, assuming one 8-hour shift: crusher, 360kWh; washing, 160kWh; drying, 170.56 kWh; magnetising, 80 kWh; conveying, 16 kWh; screening, 0,8 kWh; and briquetting, 44 kWh (Erdwich, 2016; Kumi Solutions, 2016; Walker Magnetics, 2016; Briklis, 2016). Waste treatment costs are taken as R1,63 per kilogram, as used in the case study at Hansens. Operating labour is taken as R35 per hour. One worker is required to run the operation. These values were also obtained from Hansens. The input variables and cost calculations for the wash and briquette process can be seen in Figures A.1 to A.6.

### 5.2.3 Thermal Degreasing Inputs

Scrap processing via thermal cleaning is also analysed, using data from Tables 3.3 and 3.4. These values need to be adjusted for time, as the cost estimates are from 2001. The plant has a capacity of 25kt per annum, which means that adjustments have to be made in this respect as well. It is adjusted to the size of the smallest principle producer of ferrotitanium according to Roskill Information Services Ltd (2013), which is around 800 000 kg per annum. It is estimated that three workers are required to run the process, because of its larger scale. Additional values are assumed to be identical to that of the scrap processing described above. A full list of the feasibility study calculations and inputs are given in Figures A.7 to A.12.

### 5.2.4 Ferrotitanium Inputs

The same processing values are used as described in the scrap washing and briquetting section. An induction furnace quote was obtained from Saveway Furnace Monitoring. A 250 kW, 200 kg coreless or crucible induction furnace was quoted to cost between 220 000 and 250 000 Euros from a supplier in Germany. This includes components such as the tilt rotary components, power pack, hydraulics, tilting frame, furnace frame and crucible, and manual hood. It is assumed that two workers are required for the furnace and one to process the scrap. Their wage is taken as an average of the wage paid to scrap processors and operators of furnace equipment. Selling price for ferrotitanium is taken at \$5.90 per kg. It is assumed that 75% titanium ferrotitanium is made, which requires the addition of 25% ferrous scrap. The cost of this is taken at \$0.25 per kilogram, as sourced from Metalprices.com (2016) for shredded ferrous scrap. Figures A.13 to A.18 show all feasibility calculations and inputs for the production of ferrotitanium.

### 5.2.5 Vacuum Arc Remelting (VAR) Inputs

Melting via VAR requires the addition of titanium sponge. With no local sponge production capacity, this needs to be imported. It is assumed that 75% sponge and 25% scrap is used, as is used by RTI, according to Roskill Information Services Ltd (2013). A value of $7.78 per kg is used for titanium sponge, which is the price from China, according to Metalprices.com (2016). Equipment costs are taken from Sampath (2005), as shown in Table 3.5, and adjusted to a capacity of 600 000 kg per annum. The data is also adjusted for time, as the study was done in 2005. Electricity usage is assumed to be 100 kWh, as described in Sampath (2005). The source states that two labourers are required, but according to industry expert, Scott Jackson, that number will be higher in reality. It is thus assumed to be around 6. Their rate is given at $14.10. While a double VAR process is described by Sampath (2005), only one VAR melter is assumed in the analysis as the investment costs are so high. This will mean that throughput is halved, as the melt needs to be repeated, which leads to the process having a 200kg/hr throughput. Waste treatment is taken as the same amount used in processing, but multiplied by 25%, as only a quarter of raw materials are contaminated. A full list of input variables and calculations for this process can be seen in Figures A.19 to A.24.

### 5.2.6 Electron Beam Cold Hearth Melting (EB CHM) Inputs

EB CHM uses data from the same source as VAR. This data is shown in Table 3.7. While alloying additions are required due to melt losses, it is assumed that 100% scrap is used as feedstock material. The process has a throughput of 700 kg per hour and again is adjusted for size to 600 000 kg per annum. Time adjustments are also made as with previous processes. The remaining input values are taken to be the same as VAR. The input variables and feasibility study calculations can be seen in Figures A.25 to A.30.

### 5.2.7 Plasma Arc Cold Hearth Melting (PA CHM) Inputs

PA CHM utilises the same input data as EB CHM. The same adjustments are also made to account for capacity and time. Equipment costs and throughput values are taken from Table 3.8. PA CHM's full feasibility study calculations and inputs variables are shown in Figures A.31 to A.36.

### 5.2.8 Mill Product Production Inputs

As EB CHM is the most efficient process to produce melted products, having the highest throughput, it is used as the precursor to mill product production. Equipment cost data is taken from Table 2.5. It is assumed that four additional labourers are required. The cost calculations and input variables for producing titanium mill products are given in Figures A.37 to A.42.

### 5.2.9 Precision Casting Inputs

A quote was obtained from ALD Vacuum Technologies in Germany for their smallest model, the Leicomelt 2. It is quoted at 1,1 million Euros, which includes shipping to South Africa. This model allows the production of titanium castings to be produced from up to 100% scrap. Expensive intermediate processes, used to produce ingots and mill products are removed, which allow near-net shape castings to be produced directly from scrap. This process is combined with initial scrap processing, as clean briquetted scrap is required. The Leicomelt 2 is specially suited for the melting of titanium and can be used to produce biomedical components or recreational products, such as titanium golf clubs. The furnace requires 7 kW to operate, has a maximum melting capacity of $2l$, with castings weighing up to 8 kg. It is assumed that products can be sold at R1000 per kg, which is a conservative estimate, given that most titanium golf drivers sell for over R3000, while weighing about 0.2kg. Two operators are needed to manage the furnace and one for scrap processing. Their wages are again assumed to be the average of a scrap processor's wage and the wage obtained by a furnace operator. Figures A.43 to A.48 show the input variables used and cost calculations for the feasibility study of precision casting.

### 5.2.10 Benchmark Components

The benchmark components used in this study were supplied to the titanium project by Aerosud and Daliff Engineering. The production processes of these components were optimised by projects at Stellenbosch University to result in improved machine time and reduced material waste. All components are for use in aerospace applications, either for integral components in construction or supporting components. The banana-brace, intercostal and wing riblet are manufactured by Aerosud for use in the Airbus A400M.

A forming-machining process combination was used for the banana-brace, while the intercostal demonstrated the production of thin walled components. The so-called knuckleduster is a product manufactured by Daliff Engineering, produced by a press-and-sinter operation, followed by a machining operation. The amount of scrap generated from each of these parts is shown in this section by utilising their worksheets. The full volume removed per process step can be seen in Appendix F for all four parts. The scrap creation of each part is divided into machine swarf and solids where applicable. As this study focusses on machine chips, otherwise known as swarf or turnings, only these are taken into account and the solid scrap is ignored. Once the amount of loose scrap produced by each part has been calculated, the data for each part can be fed into the feasibility model. From this, the number needed to be produced to create enough scrap for recycling can be calculated. This can then be compared to real-world production forecasts, and used to give credibility to the model.

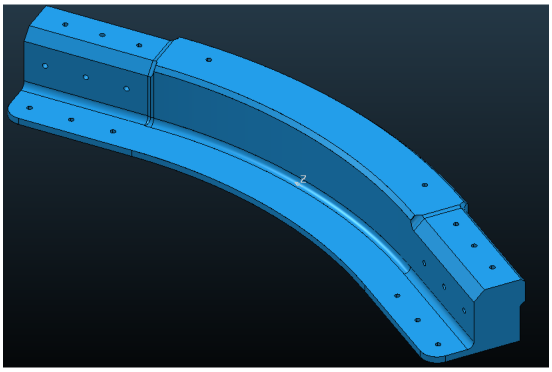

**Figure 5.11:** CAD Model of the Banana-Brace

The optimisation of the banana-brace production process involved the introduction of a forming operation before the machining steps to reduce the size of the blank were required. The resulting blank was 2.6 kg in weight, compared to 3.1 kg in the old process, a material reduction of 24%. The machining of the part took place in two setups. Shown in Table F.1 in Appendix F is the theoretical scrap created with each cut of the banana-brace. This is summarised in Table 5.4. By utilising the volume of swarf created and the density of titanium, the weight of the produced scrap is calculated. The theoretical weight of scrap produced from one banana-brace is about 1.98 kg. This means that about 76.2% of the original volume is reduced to scrap, all in the form of machine turnings.

| Scrap Volume [$cm^3$] | Scrap Weight [kg] | Scrap Rate [%] |
|---|---|---|
| 124.14 | 1.977 | 76.2 |

**Table 5.4:** Banana-Brace Scrap Turnings Produced

The intercostal starts with a raw titanium billet with the dimensions 502 × 326 × 30 mm, which has a volume of 4 906 420 $mm^3$. As can be seen from Table F.2 in Appendix F, the machining of the intercostal produces almost 20kg of scrap. Unlike the banana-brace, solid scrap is produced in the form of the two centre plugs and has supports on both sides. Figure 5.12 shows the intercostal's CAD model, from which one can see the holes left where the centre plugs were removed. Almost 4 500 $cm^3$ of scrap is removed from the blank, which means the scrap rate of the part is 91.34%. Of this scrap, nearly 3800 $cm^3$ (17kg or 77.42%) comes in the form of turnings. The amount of turnings produced from machining the intercostal is summarised in Table 5.5.

| Scrap Volume [$cm^3$] | Scrap Weight [kg] | Scrap Rate [%] |
|---|---|---|
| 3798.74 | 16.828 | 77.42 |

**Table 5.5:** Intercostal Scrap Turnings Produced

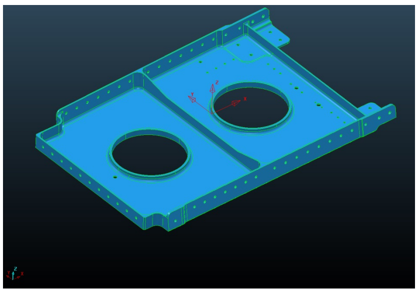

**Figure 5.12:** CAD Model of Intercostal

The wing riblet, seen in Figure 5.13, is machined from a titanium billet, with the dimensions 400 × 300 × 43.5 mm. This raw material has a volume of 5 220 000 $mm^3$. A second setup is done, which starts with a volume of 9 396 000 $mm^3$, as it includes the volume of the fixture plate, with the dimensions 400 × 300 × 58 mm. The volumes removed for steps 1 to 18 of setup 1, and steps 1 to 17 of setup 2 are shown in Table F.3 in Appendix F.

| Scrap Volume [$cm^3$] | Scrap Weight [kg] | Scrap Rate [%] |
|---|---|---|
| 3 750.25 | 16.614 | 71.84 |

**Table 5.6:** Wing Riblet Scrap Turnings Produced

The summarised amount of turnings produced from machining the wing riblet is shown in Table 5.6. A similar amount of turnings to the intercostal is produced at about 16.6kg per part. As the machine sheet includes the fixtures and solids of the wing riblet in its final volume, it is difficult to estimate the scrap rate of the part, however it is sure to be above 90%. The percentage of turnings to the original fixture is 71.84%.

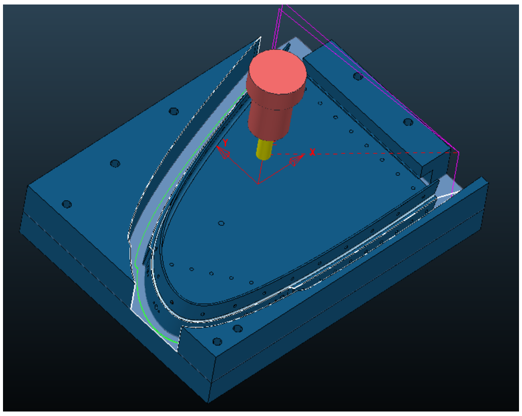

**Figure 5.13:** CAD Model of the Wing Riblet

The knuckleduster is shown in Figure 5.14. It is also machined in two setups, starting with a billet of the dimensions $100 \times 110 \times 50$ mm and thus a total volume of 549 509.22 $mm^3$. Table 5.7 shows the total volume and weight of scrap produced in the production of the knuckleduster. See Appendix F for detailed information.

| Scrap Volume [$cm^3$] | Scrap Weight [kg] | Scrap Rate [%] |
|---|---|---|
| 501.62 | 2.222 | 69.73 |

**Table 5.7:** Knuckleduster Scrap Turnings Produced

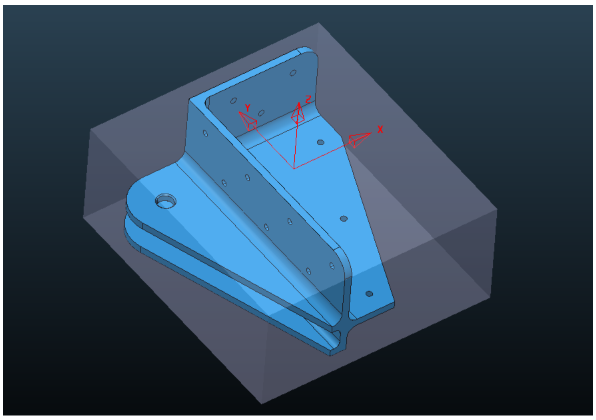

**Figure 5.14:** CAD Model of the Knuckleduster

## 5.3 Monte-Carlo Simulation

The best alternative remaining after the feasibility study is subjected to an in-depth study by simulation. This alternative is modelled to include the entire range of possible costs, using the minimum and maximum multiplication and Lang Factors previously used. This allows uncertainty to be introduced into the models, as described in Section 4.5.

A Monte-Carlo simulation model is incorporated into the analysis of the remaining alternative. Using the @Risk tool, distributions can be fitted to the majority of the inputs for the model. Triangular distributions are used for the majority of inputs, as the minimum, maximum and most likely values are given by the ranges of the multiplication factors used to estimate costs. This makes it simple to introduce fairly accurate distributions into the model. Where sufficient historical data is available, a custom distribution can be fitted to the data. The best fitting distributions are used in these cases. This allows one to then analyse the probability of each project to be profitable and make a certain amount of money.

Sensitivity Analysis is done, which shows the influence of each variable on the final NPV. Equation 4.5.2 and 4.5.3 explain how the @Risk tool estimates sensitivity. The results of the Sensitivity Analysis are displayed in a tornado graph, which ranks the inputs from highest to lowest influence on the NPV.

Using results from the simulation, the probability of being profitable from South Africa's titanium scrap is determined. The profit margin is varied over simulations to see the influence on the probability of being profitable. A final simulation is run with a fixed selling price, to analyse its effect on NPV and sensitivity of the model. Ten-thousand iterations are run for each of the four simulated cases. A full list of the simulation model's inputs can be seen in Appendix C.

### 5.3.1 Determining Distributions of Inputs

Distributions are calculated for all input variables which are expected to undergo a significant variation over the analysis period. The supply of titanium scrap, exchange rates, electricity rates, and prices of titanium scrap metal are some examples of the inputs which undergo significant variation and to which distributions are fitted.

As used in the feasibility study's pessimistic scrap estimate, the historical scrap export data is taken as an indicator of the amount of scrap available. The secondary method of predicting the scrap quantity is not used, as it relies too heavily on assumptions. A distribution has been fitted to the data since 2005, as seen in Figure 5.15.

The fit is chosen by an Akaike Information Criterion (AIC) score, which is the least for an exponential distribution. This indicates the best fit above other distributions. The resulting equation is used to predict scrap exports in the future, and thus estimate the amount of scrap available for recycling. As can be seen from Figure 5.15, there is a 91.3% chance of predicting a value between 939 kg and 147 500 kg. Both data sets (simulated and real) have a mean of about 55 469 kg. The distribution allows the erratic nature of scrap availability to be simulated so it is possible to see how the financial analysis will

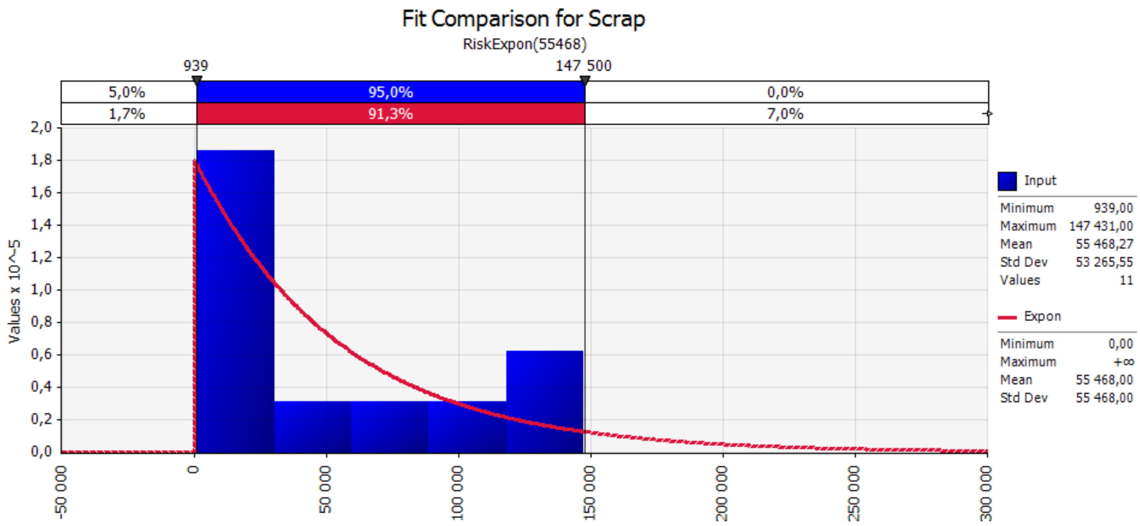


**Figure 5.15:** Distribution Fitted to Scrap Exported

cope with outlier years, where little or no scrap is available for recycling.

Exchange rates are predicted slightly differently. If one only looks at the past data of Dollar to Rand exchange rates for example, one would predict only values between R7.60 per Dollar and R15.15 per Dollar. On top of that, the data set is for monthly exchange rates since 2013, obtained from Standard Bank, and in this time the majority of values are under R10. Thus, when a distribution is fitted onto the data set, there will be a greater chance of predicting a Rand-Dollar exchange rate of under R10 per Dollar. This is clearly not realistic, as at the time of the study, the price was over R15 per Dollar and expected to rise. Furthermore, this would result in exchange rates which are not dependant on previous rates. The monthly rise or fall in value is thus calculated and a distribution is fitted to this data, which would predict the probability of a rise or a fall by a certain amount.

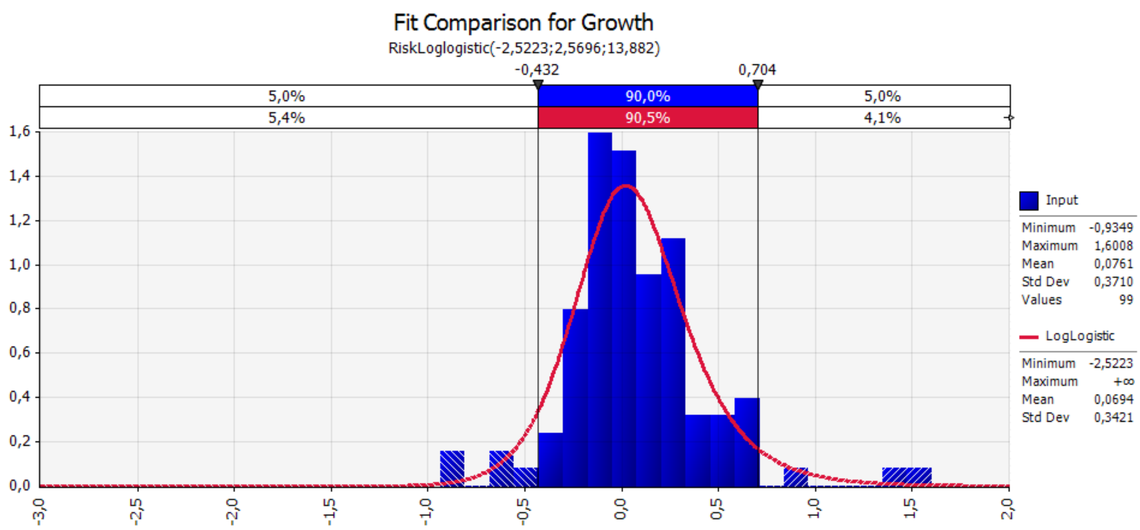


**Figure 5.16:** Distribution Fitted to Rand-Dollar Exchange Rate Change

A Loglogistic distribution was chosen, as it had the second best AIC score behind a Laplace distribution. As seen from Figure 5.16, the resulting distribution has a 90.5% chance of producing values between -0.432 and 0.704, with a mean of 0.0694. This means that the future monthly exchange rates will have a 90.5% chance of having a value of the current exchange rate plus 70 cents or minus 43 cents. Using this method, the future values start with the current exchange rate and the up or down movements are simulated for each month in the future. Thereby, it simulates the variability in exchange rates, while having a greater tendency to move upwards than downwards, which is more realistic. The Laplace distribution was not chosen as it resulted in too many negative values, and thus results in unrealistic expected values.

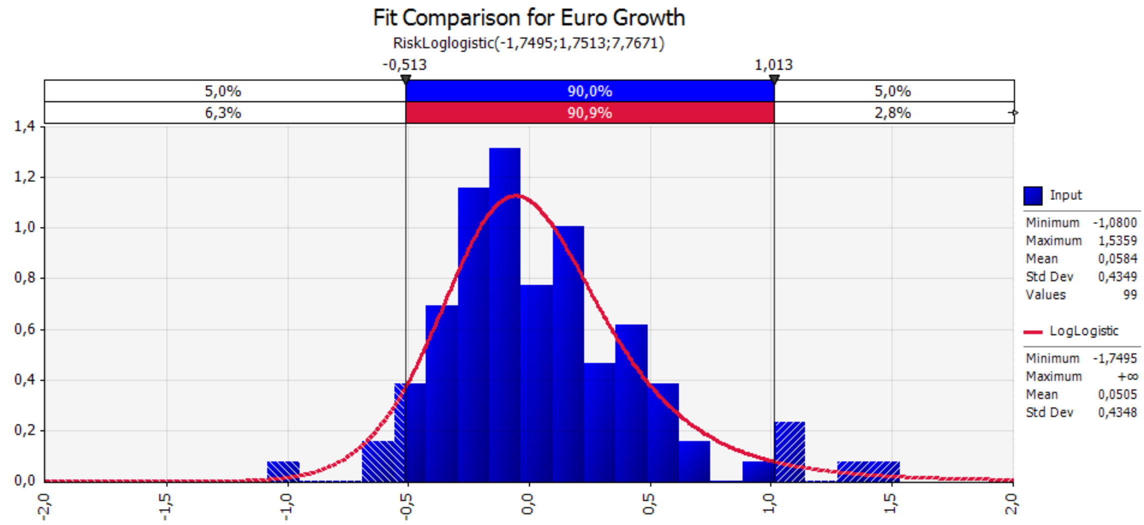


**Figure 5.17:** Distribution Fitted to Rand-Euro Exchange Rate Change

The Rand-Euro exchange rate was simulated in the same fashion. The resulting distribution is also a Loglogistic distribution, as seen in Figure 5.17. It has a 90.9% chance of producing monthly changes in a range minus 0.513 to plus 1.013. The Loglogistic distribution was chosen because it has the best fit according to the AIC score.

Electricity costs are based on past rates obtained from Eskom. The average rate for the industrial sector was taken since the year 2003. Similarly to the exchange rates, the yearly change was modelled, rather than the outright electricity rate, to model the growth and decline in prices.

The resulting distribution is a uniform distribution, with minimum possible change of -0,867c per kWh and a maximum rise of about 8c per kWh. This is used to simulate future electricity prices from the current 63c per kWh, based on the industrial sector average electricity cost at the time of the study.

Historical data on titanium scrap prices are difficult to come by, and erratic in nature. According to Roskill Information Services Ltd (2013), scrap prices usually rise and fall with the demand for ferrotitanium. As stated in Section 3.9, the price moves up and down considerably. The January price of aero quality titanium turnings for each year

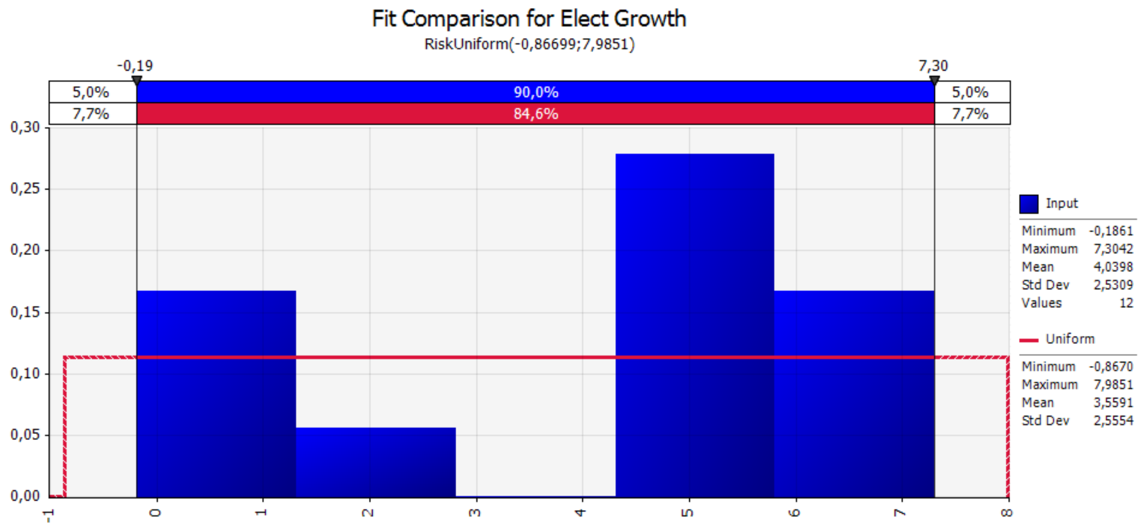


**Figure 5.18:** Distribution Fitted to the Change in Electricity Prices for the Industrial Sector

between 1993 and 2013 was taken as a dataset. These values were obtained from Roskill Information Services Ltd (2013), and then adjusted for UK inflation, as to normalise it to a 2016 equivalent. An average was taken of the high and low prices and a distribution fitted on the resulting dataset. South African titanium scrap prices are not used, as no dataset is available with this data.

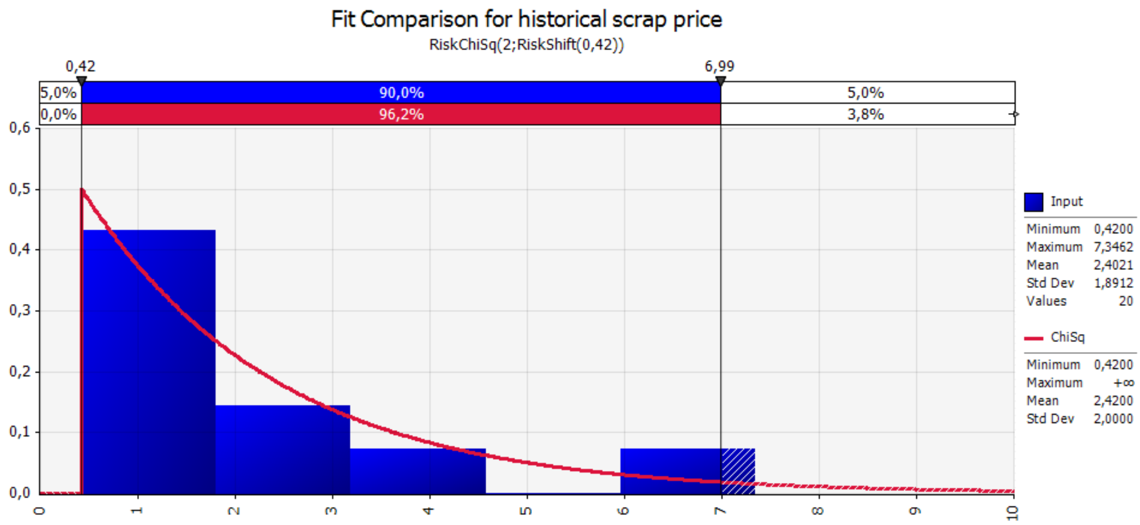


**Figure 5.19:** Distribution Fitted to the Adjusted Scrap Price Between 1993 and 2013

The resulting distribution is a Chi-square distribution with a minimum value of 0.42 ($ per pound) and a mean of 2.42. This is illustrated in Figure 5.19. The scrap price was not modelled using the yearly change, as the erratic behaviour of the scrap market causes high variance in the price and consecutive years are often not dependant on each other. The large variance also causes high drops in scrap prices, causing the price to fall below 0, which is impossible.

Historical data was obtained from the South African Reserve Bank on interest rates in South Africa since 2010. The total yearly change in interest rate was determined from this data and a distribution fitted on this. The result is a uniform distribution, as seen in Figure 5.20.

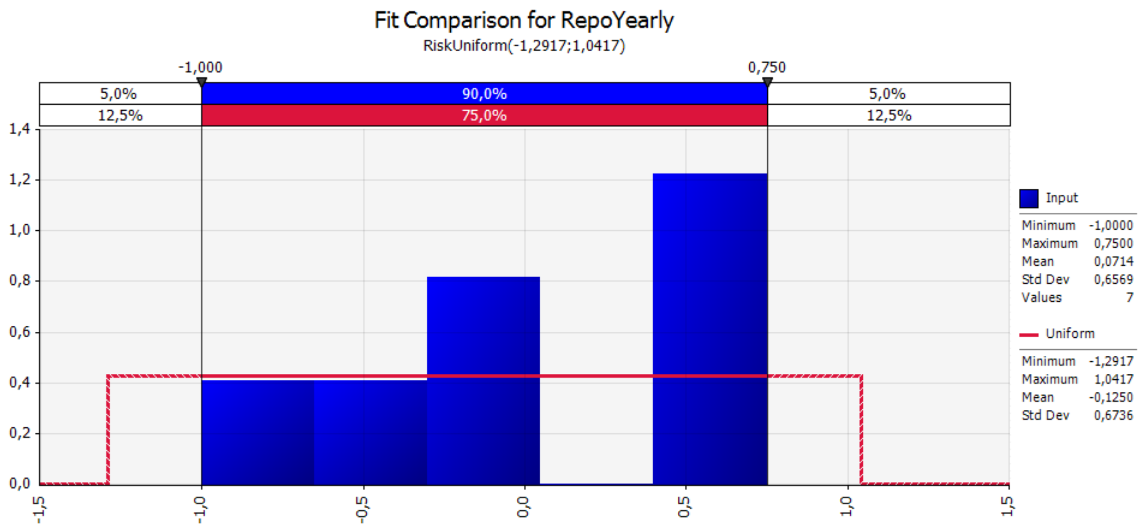


**Figure 5.20:** Distribution Fitted to Yearly Interest Rate Changes in South Africa

Because, historically, the interest rate moves up or down in factors of 25 basis points, the distribution is rounded to 0.25%. It is then simulated for each year in the future and added or subtracted from the previous year's interest rate.

The remainder of the inputs were varied over the range for each individual manufacturing cost as shown in Tables 4.7 to 4.9. Triangular distributions were fitted onto these using the minimum and maximum values of the range, with the midpoint used as the most likely value. These values were simulated individually for each year so that the same manufacturing values are not used for every year in a single simulation. Additionally, the initial fixed capital investment amount is varied over the range shown in Table 4.10. As the efficiency of a smelting and general recycling process is not 100%, the output is varied by between 70% and 90%, based on experience gained from the background study.

### 5.3.2 Equipment and Other Costs

The equipment used in the simulation are the scrap processing equipment, as described in Chapter 5.2.2 and a smaller furnace used for precision casting. A quote for this was obtained from Linn-High-Therm in Germany and can be seen in Appendix E. While the majority of input variables are determined by the factorial method, the operating supplies in a precision casting are more than that projected by the factorial method. This is because of the use of expensive crucibles to melt the metal in. Graphite crucibles are used in the simulation at a cost of 41.40 Euros per piece, as quoted in Appendix E.

Linn-High-Therm specified that a graphite crucible can be used in ten castings, after which it has to be replaced. The water use for the furnace is given as 8 litres per minute. It is assumed that argon gas is flushed through the furnace twice before each melt. According to Afrox, argon gas in Stellenbosch sells for R600 per cylinder plus R250 to hire the 17.4 kg cylinder. The volume of argon required to flush the furnace is taken as the volume of the cuvette that can fit in the furnace.

### 5.3.3 Additional Process Parameters

The simulation is run three times, with 10 000 iterations each, with a varying profit margin. A final simulation is performed using fixed selling prices instead of a margin. The melt rate of the furnace is a maximum of 60 seconds, but to account for the furnace to flush with argon, and setup and cooldown time, it is assumed that each part takes 10 minutes. The amount of scrap processed is thus determined by the volume of scrap in the country and the throughput of the system. The lowest of the two is taken for each year. This allows one to simulate the erratic nature of the availability of scrap and see how a process would react to this.

# Chapter 6

# Experimental Results and Discussion

In this section the results of the background study, feasibility study and simulation are given. The background study is described in Chapter 5, with its results and lessons learned being summarised in this chapter. The feasibility study results are given as a break-even analysis and scenario analysis. A feasibility framework is created from the results of the feasibility model. Finally, the results of the Monte-Carlo simulation model are given and the best course of action for titanium recycling in South Africa at present is discussed.

## 6.1 Background Study Results

As stated in Chapter 5, the results obtained from the background study at Hansens were evaluated in terms of capital investment costs, scrap value creation, lubrication costs and environmental impact. The results found are discussed in greater detail in this chapter. The lessons learned about the current waste-to-resource strategies at Hansens and their planned future strategies, are also discussed.

The quality of scrap is only put into two categories by Hansens, namely loose swarf and briquetted swarf, as this is the only measure that determines the value assigned to it. The briquettes from the processes were analysed to identify any possible improvements in packing density. The density of the benchmark briquette (Figure 3.9), given to Hansens by the manufacturer of briquetting equipment was calculated to be 1.99 g/cm$^3$, consistent with the 2 g/cm$^3$ industry standard found in the literature review.

Briquettes from Turning Cell 3 and the new prototype machine were found to be less dense. Their densities were calculated to be around 1.67 g/cm$^3$ and 1.59 g/cm$^3$ respectively. Although the buyer will not pay extra if the briquettes are compacted more tightly, it may mean that they could fit up to 20% more scrap in a shipment, possibly reducing transportation costs. The analysis of a briquette from Turning Cell 3 can be seen in Figure 6.1.

Contrary to what the literature says, it was found that lubrication costs, using flood cooling and MQL are very similar per part. MQL still provides less effort in terms of treatment and disposal of lubrication fluid, and also improved scrap quality. As seen in Figure 6.2, the lubrication costs for turning cell 3 are marginally higher than that of the Daewoo 2. This is primarily due to its increased throughput rate. Both methods' lubrication costs are calculated to be around 2c per part, and as Turning Cell 3's machines

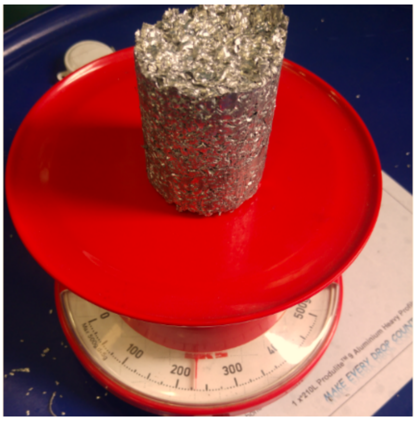

**Figure 6.1:** Analysing Briquette from Turning Cell 3

produce more parts per shift, more money is spent on lubrication. As the throughput is increased, a greater amount of scrap per shift is also created, with the added ability to briquette the swarf. Because of this, the value of swarf produced from Turning Cell 3 is more than double that of the Daewoo 2, as shown in Figure 6.3. This is further improved in the new prototype machine. Because dry cooling may be implemented, no money is spent on coolant, and with a further increase in throughput rate, the value of scrap is above R800 per shift, per machine. This is impressive, as the product has traditionally been viewed as waste.

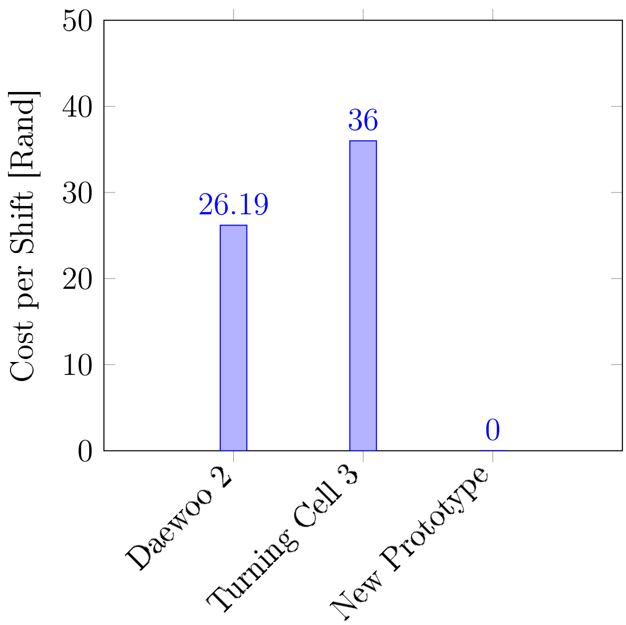


**Figure 6.2:** Lubrication Cost of Different Machine Strategies per Shift

This improvement in scrap value per shift comes at a cost. As seen in Figure 6.4, when compared to the Daewoo 2, Turning Cell 3's machines have a 149% increase in investment price. The new prototype machines, while also more than twice as expensive than the Deawoo 2, are marginally less expensive than Turning Cell 3's machines, as there is no need to retrofit MQL and briquetting systems on them. The new prototype machine

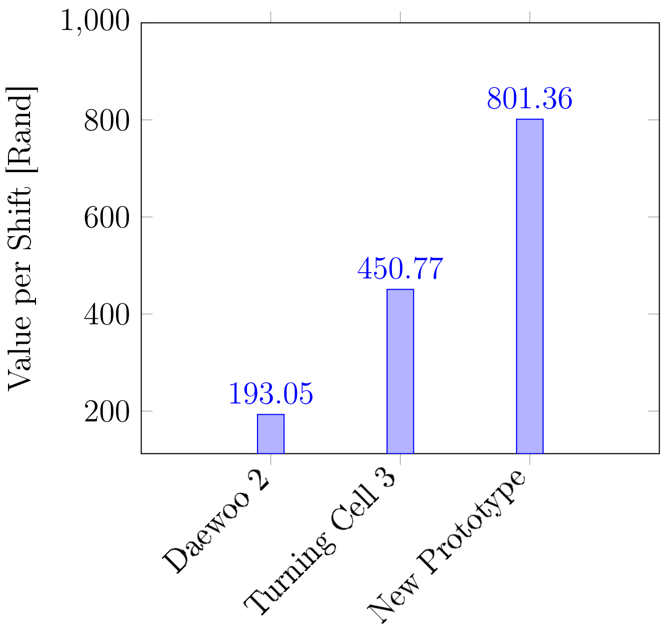


**Figure 6.3:** Scrap Value of Different Machine Strategies per Shift

will compensate for the difference in price from the Daewoo 2 within a year and a half, with the value created from its scrap alone. The value of the scrap created from the new prototype machine will cover the entire machine investment cost within 2 years and 4 months (assuming regular operating times and business days only).

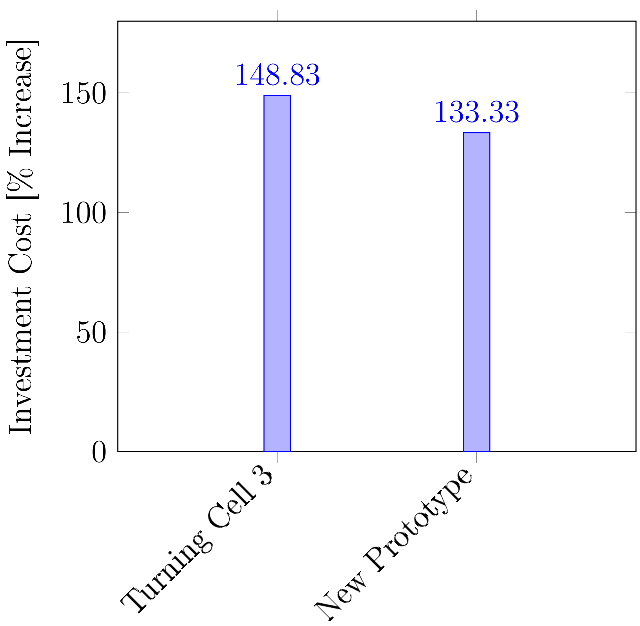


**Figure 6.4:** Comparison of Investment Costs Required Relative to Daewoo 2

Hansens has made considerable improvements to reduce the amount of waste in their processes. Waste processing and handling strategies have allowed them to maintain an edge over their competition. The engineers at Hansens stated multiple times that, as they essentially produce their parts at cost price, their scrap is their main source of profit. In terms of new scrap handling, Hansens have reached a level that will be difficult to improve on. They are thus looking to further improve the value of scrap by in-house metal production, completing the materials cycle. Instead of new scrap flowing from their process to end-of-life and raw materials production steps, recycled new scrap can be processed to raw materials in-house. This will reduce the reliance on raw materials produced from natural resources and their own scrap, and reduce residues resulting from their process. If implemented, a true in-house waste-to-resource process will be realised, where their scrap is turned directly into the raw material required for their process. An example of this adapted materials flow cycle is seen in Figure 6.5, where the new scrap flows into a new in-house raw materials production process, returning metals and alloys which are usually only obtainable from external production processes.

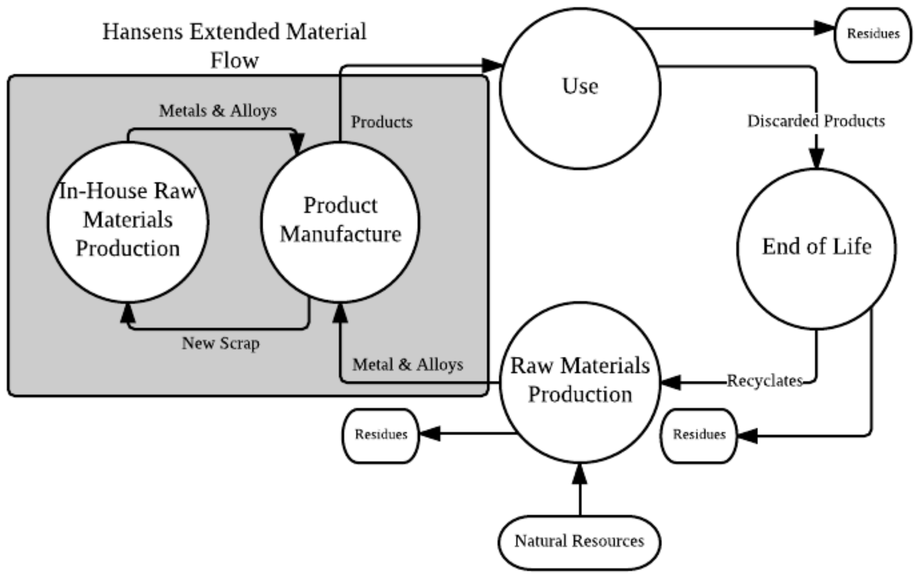


**Figure 6.5:** Outlook for In-House Recycling at Hansens

## 6.2 Feasibility Study Results

The feasibility results are given in the form of break-even analysis and scenario analysis. Break-even analysis makes use of Excel's Goal Seek function to see at which yearly throughput each recycling method breaks even, over a ten year analysis period. Using this, the feasibility framework is compiled. An illustrative case study is then performed on the break-even analysis with the use of benchmark components. Scenario analysis is used to assess the best, worst and average-case scenarios, based on probable scrap availability. This provides a good idea of the relative profitability of all the recycling alternatives available. The complete list of inputs and model calculations for the feasibility study can be seen in Appendix A. The full NPV analysis results for break-even analysis and scenario analysis are presented in Appendix B.

### 6.2.1 Break-Even Analysis

Given all the inputs described in Chapter 5, the 10-year break-even points of all the processes were calculated. For the first case, where scrap is sold as clean briquettes, it is seen that a yearly throughput of 69 098.38 kg scrap is required. This requires the process to operate at a throughput of 34.69 kg per hour, working one shift per day. The NPV analysis at the break-even rate for scrap washing and briquetting can be seen in Figure B.1 in Appendix B.

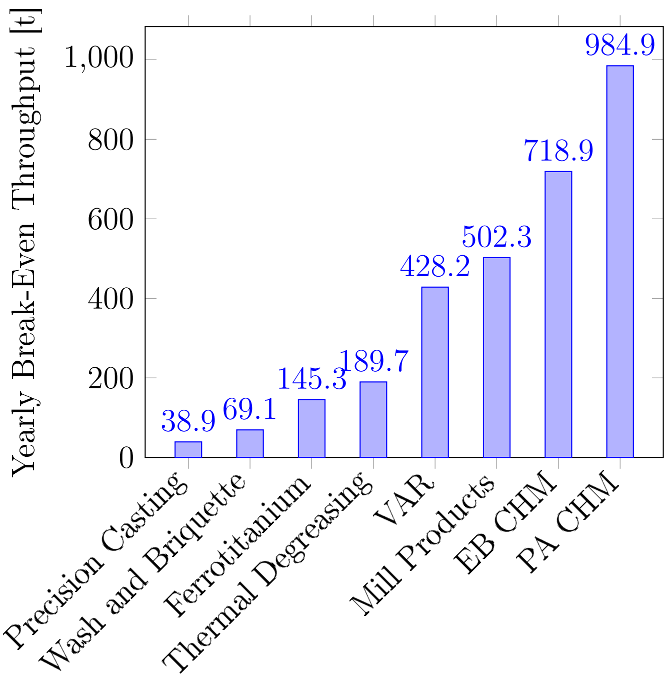


**Figure 6.6:** Comparison of Break-Even Rate of Recycling Alternatives

Thermal degreasing has a much higher throughput requirement of 180.72 kg, as the process is based on a large-scale process. With this method, clean ferrograde scrap is sold, which has a much lower selling price than briquetted aero-grade titanium swarf. This means that a higher throughput is required, because of the smaller profit margin. This equates to an hourly throughput of about 95.24 kg per hour with one daily shift or a yearly total of about 189 000 kg. Ferrotitanium becomes feasible at a throughput of 193 759.48 kg per annum, of which 145 319.61 kg is titanium scrap, while the remainder consists of ferrous scrap. The break-even NPV analyses can be seen in Figure B.5 and B.9 for thermal degreasing and ferrotitanium production respectively.

The four large-scale recycling routes require massive throughputs to be feasible. VAR requires a throughput of 1 712 873.1 kg per annum. 75% of this consists of imported sponge, and thus at about 428 218.27 kg scrap, per annum, recycling via VAR would be possible. Large scale recycling using a VAR process is infeasible without a local sponge source. PA CHM requires 984 851.61 kg scrap per annum, while EB CHM requires less, 718 867.43 kg, because of its marginally lower investment cost and higher throughput rate. Large scale mill product production, using local scrap, requires less scrap than EB

CHM and PA CHM to break even, because of the higher value added in producing plates. About 502 300 kg is required per annum to justify mill product production using titanium scrap. This is considerably less than the others and leads one to conclude that, if large-scale recycling is implemented, extra investment should be made to process the scrap to mill products. The full NPV analysis at these throughput rates can be seen in Appendix B in Figures B.13, B.17, B.21 and B.25 respectively.

Precision castings breaks even at 38 900.86 kg. The high value added and relatively low investment costs allow it to be feasible with a low amount of scrap, as a near-net shape product is produced. Its break-even NPV analysis can be seen in Figure B.29. The yearly break-even throughput rates are summarised in Figure 6.6. It shows the break-even throughput required, sorted from smallest to largest, for each method of recycling titanium.

### 6.2.2 A Feasibility Framework for Titanium Recycling

Using break-even values, combined with general knowledge about titanium recycling, a decision-making framework is compiled. The framework can be seen in Figure 6.7. The process flow starts with the production of titanium swarf in the fabrication process. At 50 kg scrap availability or more, gathering of titanium scrap becomes feasible. This is based on the amount of scrap which is stockpiled before being recycled at the STC-LAM. At this point logistics costs for shipping to a scrap dealer becomes economically feasible.

When 69.1 tonnes scrap available per annum, washing and briquetting scrap becomes a viable option. Scrap is then sold at titanium briquette price, and no longer at a general non-ferrous or aluminium price. Because of the economy of scale, large-scale melting operations are given priority choice in the framework. It thus starts by checking whether cold hearth melting is feasible. Only EB CHM is checked, as it has a considerably lower break-even point and produces the same product. This becomes feasible at 718.9 tonnes of scrap available per year. If this is true, scrap can be processed to slabs. This provides the best-case scenario, as it will eliminate impurities and contaminants in the melt, because of CHM's refining capabilities.

CHM is given priority choice above VAR because of this. As stated above, VAR will not become feasible until a local sponge source is available, and is thus used as the feasibility check for VAR. If true, VAR will allow the production of titanium ingots, which can be sold to mill product manufacturers.

If either VAR or CHM proves feasible, the intermediate melted products created from these processes can be processed further to produce titanium mill products, such as billets. This becomes feasible at 502.3 tonnes of scrap available. It thus requires less scrap to break even than CHM, and the check used to determine whether mill products should be created is to see whether there is sufficient capital available. This is in line with expert opinion, which recommend that one always look further upstream than the production of melted products, such as ingots.

Precision casting is already feasible in terms of scrap availability, as its break-even scrap volume is 38.9 tonnes, which is less than that of processing. The feasibility check

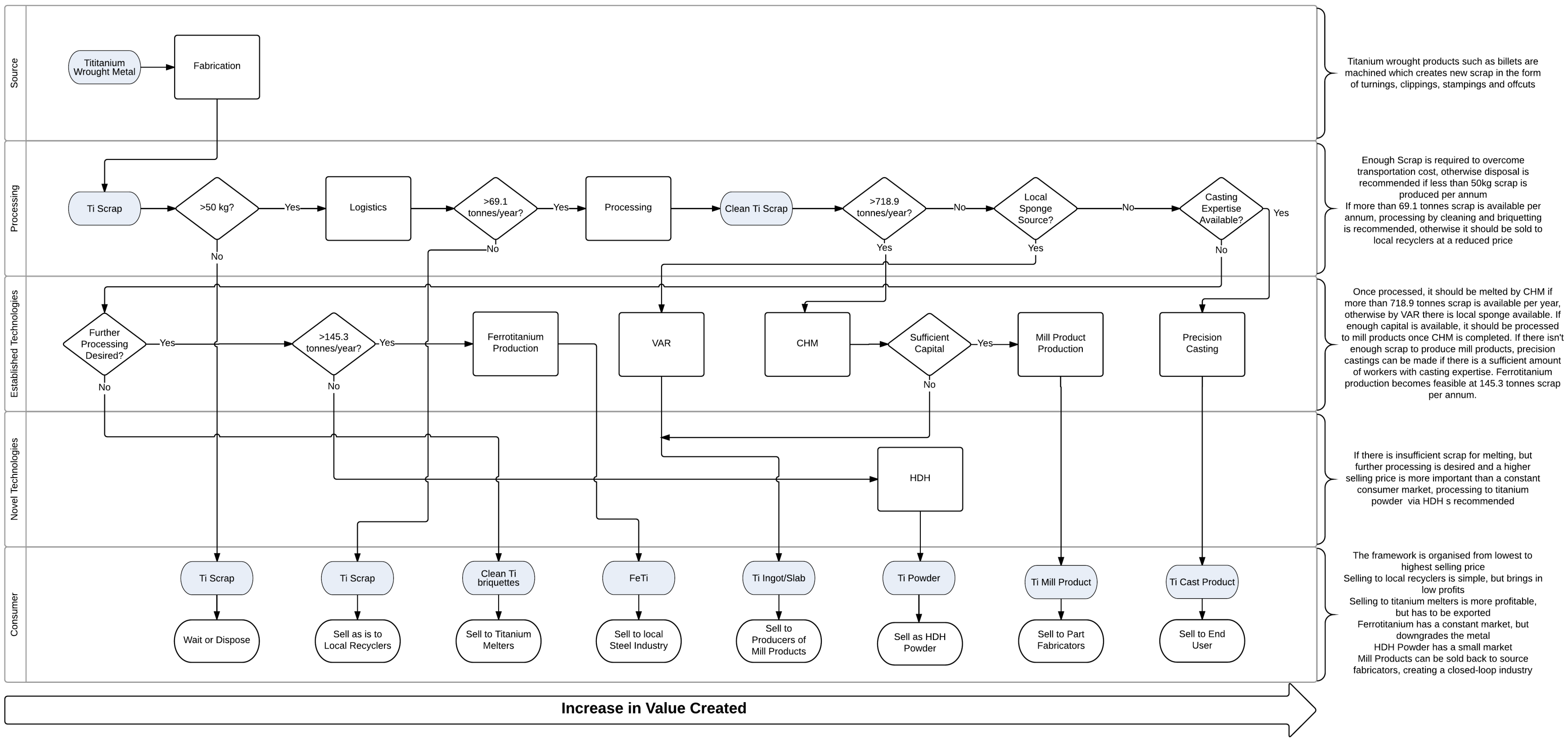


**Figure 6.7:** Feasibility Framework for Titanium Recycling

used to determine whether or not to create precision castings is thus left up to the most challenging aspect thereof, which is the technical expertise and experience required to create vacuum castings. If true, then high value vacuum cast products can be created and sold directly to end users at a high price.

If the process is deemed too complex and further processing is desired, it can either be processed to ferrotitanium or HDH powder. If no further processing is wanted, the best option would be to sell the titanium as swarf briquettes to melters abroad. Ferrotitanium production becomes feasible around 193.8 tonnes per annum, of which 145.3 tonnes is titanium scrap, while the remainder consists of iron. If this is available, ferrotitanium should be produced.

HDH powder production equipment costs are difficult to estimate, as the method is still relatively novel. As it produces a high value product, titanium powder, it will be feasible at a low scrap rate. Its novelty does, however, limit its market potential. Once the user reaches this point in the framework, HDH powder is the only remaining alternative. Recycling should thus be done through this method, or titanium recycling is infeasible in the given situation.

### 6.2.3 Illustrative Case Study with Benchmark Components

By utilising the required break-even throughput of each technology and the amount of scrap produced from each benchmark component, the required number of components to break even for each recycling process can be calculated. The results are summarised in Figure 6.8.

The figure shows the recycling methods on the left, starting with precision casting from the bottom. For each recycling process, four bar charts are seen, which shows the amount of parts which need to be produced to create enough scrap to justify recycling via that method. With precision casting, and wash and briquette processes, recycling can be feasible with as little as 2 312 and 4 106 parts produced annually, when creating the intercostal. If 2 342 and 4 159 wing riblets are produced annually, it will also make these processes feasible. As the banana-brace and knuckleduster produce less waste, considerably more are required to allow for feasible recycling using their scrap. For precision casting, the knuckleduster requires 17 506 units to be produced and 31 096 units for washing and briquetting to be justified. Similar figures are seen for the banana-brace, where 19 669 and 34 937 units need to be produced to justify precision casting and briquetting respectively.

The medium scale recycling options of thermal degreasing and ferrotitanium production require about twice to three times as many of the same units to be produced. Ferrotitanium production requires 8 635 intercostals, 8 747 wing riblets, 65 397 knuckledusters or 73 475 banana-braces to be produced annually. Thermal degreasing requires the production of 11 274 intercostals, 11 419 wing riblets, 85 377 knuckledusters or 95 922 banana-braces.

The four large-scale options, VAR, Mill Products, EB CHM and PA CHM, need massive amounts of scrap to be feasible, and thus an equally large amount of parts need

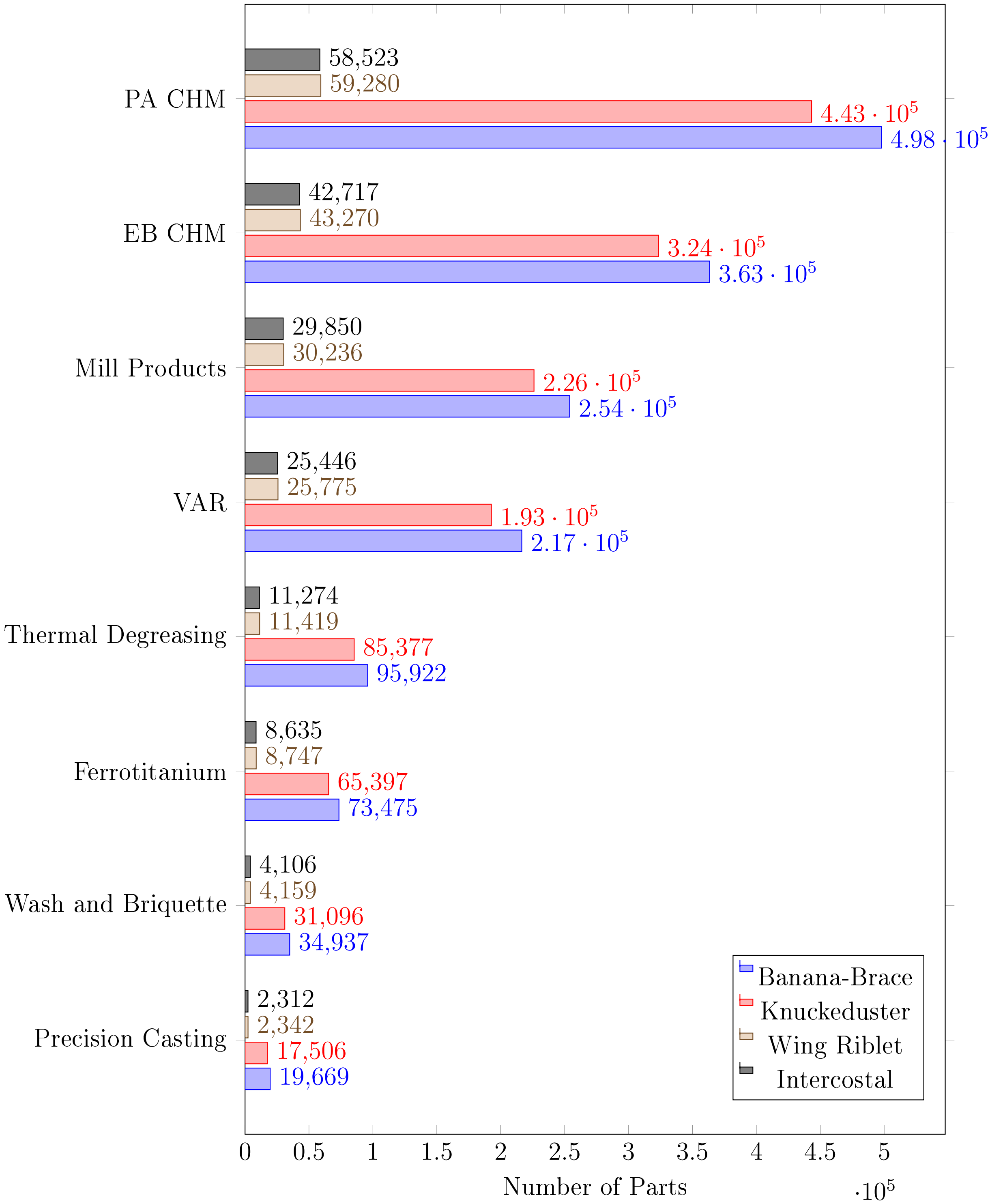


**Figure 6.8:** Required Yearly Production of Benchmark Components to Justify Recycling by Technology

to be produced. Over 190 000 banana-braces or knuckledusters need to be produced to produce enough scrap to allow for recycling via VAR, while over 25 000 intercostals or wing riblets are required to accomplish this. Mill products require the production of over 29 000 wing riblets or intercostals or, alternatively, over 220 000 banana-braces or knuckledusters. For the two cold hearth melting technologies, 42 717 and 58 523 intercostals are needed for EB CHM and PA CHM respectively. The production of 43 270 and 59 280 wing riblets is required to justify EB CHM and PA CHM. Over 320 000 knuckledusters or banana-braces are required to break even when recycling via EB CHM, while over 440 000 are required for the plasma arc version.

### 6.2.4 Scenario Analysis

The two methods for estimating the amount of scrap available in the country, described in Chapter 5, are used as the best and worst-case scenarios. The worst-case scenario is based on the exports of titanium, which gives an average available scrap of 55 468.3 kg scrap per annum available for recycling. The best-case scenario uses the mill product imports, minus articles of titanium exports. This method gives an estimated amount of 170 397.3 kg scrap available for recycling per year. A base-case is chosen at the average of these two values, 112 932.8 kg.

The net present value over a ten year period is then plotted for every recycling method in Figures 6.9 to 6.16. Positive trends indicate an increase in the project's net present value, while a downward trend shows that the project is losing money. If a project has a downward trend for any case, that case is immediately deemed infeasible. While an upward trend shows profitability, it does not automatically result in the case being classified as feasible, as the trend may level out and never reach the break-even point at a net present value of zero.

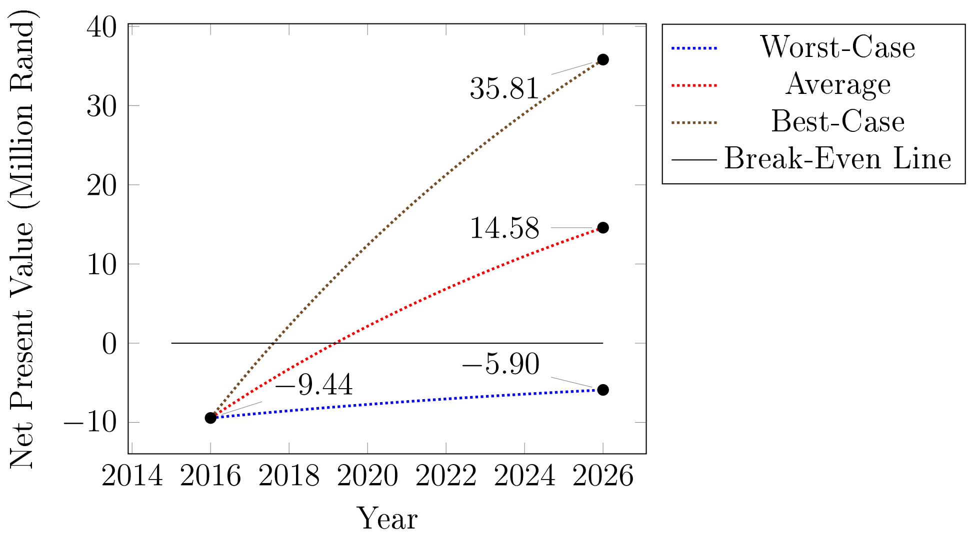


**Figure 6.9:** Scenario Analysis of Washing and Briquetting Process

Figure 6.9 shows the scenario analysis for scrap washing and briquetting. Both the best and average-cases manage to repay the loan debt within the ten year period and are profitable. A net present value of 35.81 and 14.58 million Rand is achieved, respectively. While the worst-case scenario does not pay off the loan amount in the given time period, it is still profitable as seen from the line's positive trend. It may manage to pay of the loan in the coming year or two after the analysis period. As the maximum hourly throughput of the scrap washing and briquetting process is around 50 kg per hour, the average and best-cases required 2 shifts per day to process the amount of scrap for these cases. The worst-case could be performed by only one shift per day, as the throughput requirement for this case was around 28 kg per hour. The complete NPV scenario analyses for processing to briquettes are shown in Figures B.2 to B.4.

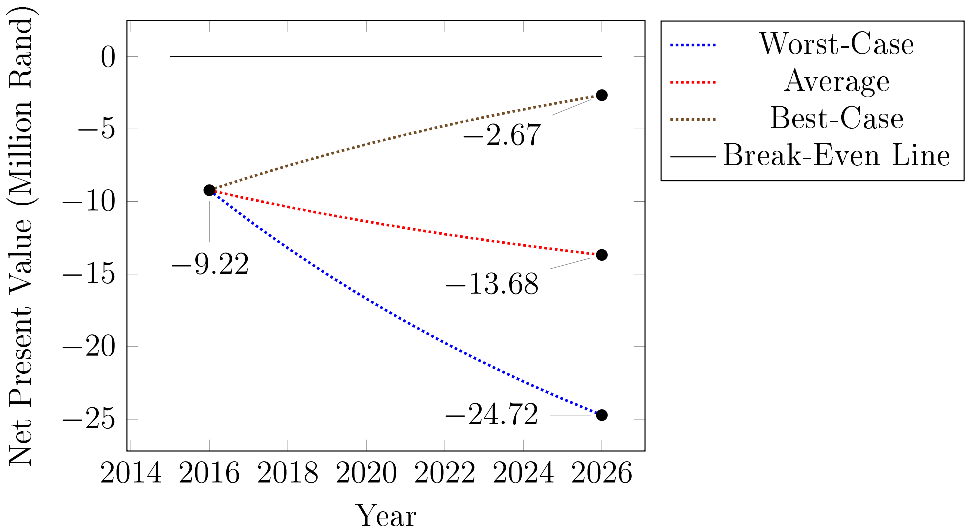


**Figure 6.10:** Scenario Analysis of Thermal Degreasing Processing

Thermal degreasing analysis is shown in Figure 6.10. None of the three cases manage to cover the loan amount in the ten year period, but have varying degrees of profitability. While the worst and average-cases have negative trends, and thus lose money quicker than it can make money, the best-case has an upward trend. The best-case has a negative NPV of R2.67 million after ten years. This case is still profitable, and may pay off its loan in the coming year or two after the analysis period. It does, however, look unlikely, as the trend levels out at the end. Thus, without an increase in selling price to account for inflation, even the best-case does not look to be sustainably feasible. All three cases of thermal degreasing are analysed with only one daily shift, as the process is capable of handling large hourly throughputs. Thermal degreasing's full NPV scenario analyses are shown in Figures B.6 to B.8.

A similar trend to thermal degreasing is seen in the analysis of ferrotitanium production in Figure 6.11. The financial scale is much larger, which is indicated by the major losses which occur in the worst-case of ferrotitanium production. The large initial investment costs and relatively low selling price are to blame for this. An NPV of -R52.52 million is seen at the worst throughput, much larger than that of thermal degreasing at -R24.72 million. Its average-case also has a negative trend, ending up with a NPV of -R34.57 million, as it is not able to cover the cost of manufacturing and loan amount with that throughput. The best-case of ferrotitanium again has an upward trend levelling out

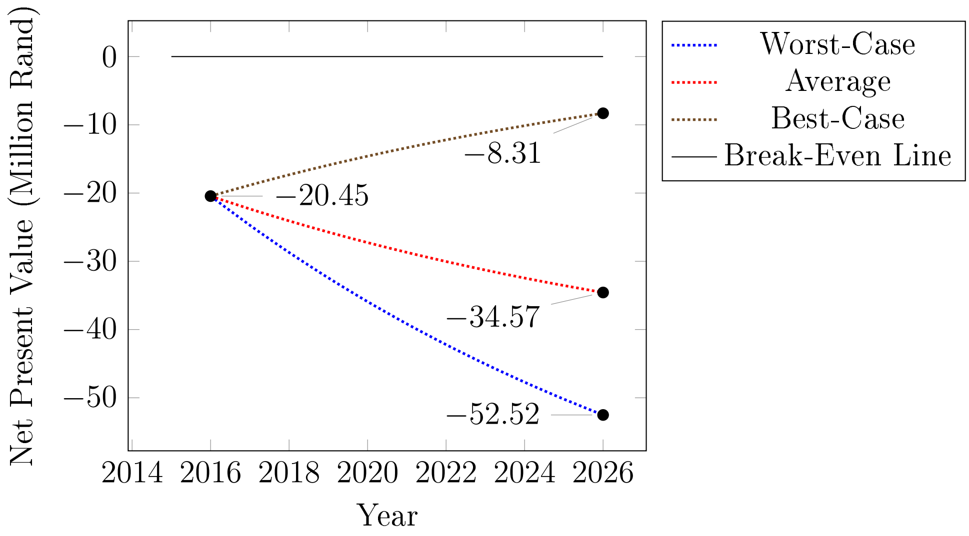


**Figure 6.11:** Scenario Analysis of Ferrotitanium Production

at the end. Its upward trend initially gives encouraging signs that the loan amount will be paid off in ten years, but fails to do so, ending with a NPV of -R8.31 million. Thus, recycling via ferrotitanium production is also not a viable option for a predefined best-case. Similar to the findings of Slatter and Barcza (1987) it can again be said that ferrotitanium production is not economically feasible without an adequate supply of titanium scrap. Similar to the washing and briquetting process, recycling through the production of ferrotitanium requires one work shift to cover the worst-case amount of scrap and 2 for the rest. This is because the equipment needed for washing is the same and acts as the bottleneck in the system. Figures B.10 to B.12 show the complete NPV scenario analyses for ferrotitanium production.

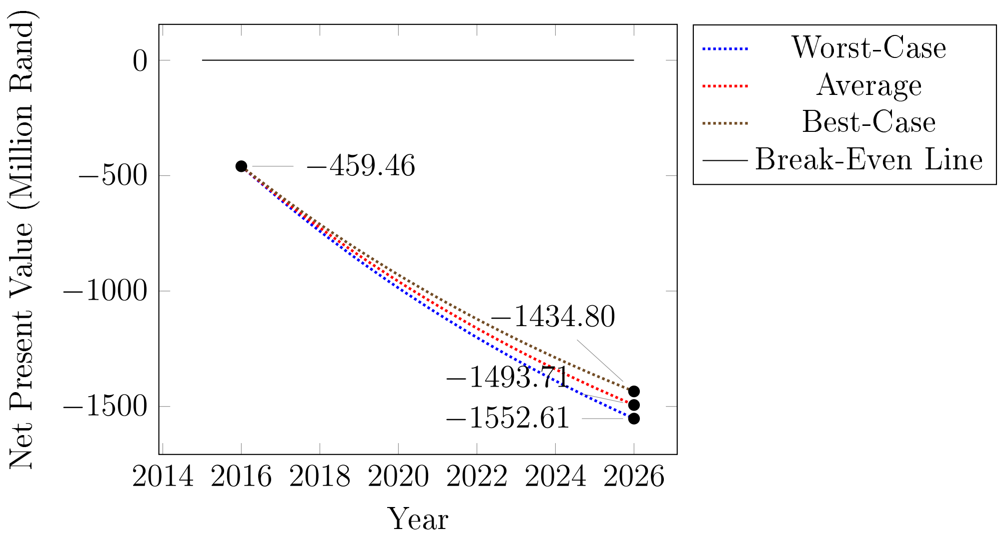


**Figure 6.12:** Scenario Analysis of VAR Melting

All four large-scale recycling methods, seen in Figures 6.12 to 6.15 incur massive losses, as expected. A steep downward trend is seen in all three cases of VAR melting, shown in Figure 6.12. All three cases end up with a negative balance of over -R1 400 million, a massive loss. At present this is completely infeasible in the given scale. VAR is particularly bad because of the additional requirement of titanium sponge to be added to the melt, which raises the process cost considerably. For all large-scale recycling methods only one daily shift is required to deal with, even in the best-case amount of scrap, as they are designed for high throughputs. VAR's full NPV scenario analyses can be seen in Figures B.14 to B.16.

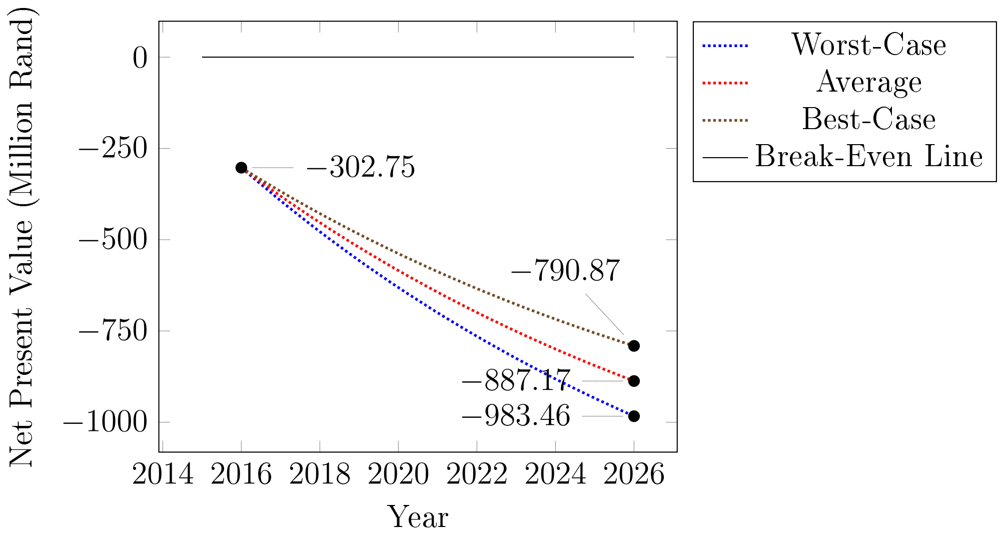


**Figure 6.13:** Scenario Analysis of EB CHM

EB and PA CHM, the analysis of which is shown in Figures 6.13 and 6.14, have similarly high losses. It can be seen that there is a greater variation in the three cases between the CHM methods and VAR. This is most likely due to the effect of sponge, necessary in VAR production. EB CHM has lower financial losses than PA CHM, with NPV values ranging between -R983.46 million and -R790.87 million, compared to -R1 414.53 million to -R1 221.93 million.

The increased selling price of titanium mill products, such as the plate scenario used in this product, does not make a significant enough difference to stop this method from ending up as the least profitable of all recycling routes. The combination of the massive initial investment required and the high cost of manufacturing leaves it with NPV ranging between -R2 102.8 million and -R1 502.33 million. The scenario analysis for the production of titanium mill products from scrap is shown in Figure 6.15.

The best option is the small scale scenarios given in precision casting of titanium components. This method has the highest NPV at the ten year mark of all recycling methods for all scenarios. The scenario analysis is shown in Figure 6.16. In the worst-case scenario, an NPV of over R81.96 million can be seen. This raises as production increases, climbing to R366.26 million for the base-case and R650.55 million for the best-case scenario. It should be noted that the facility is operating at 3 shifts per day, melting up to 28.51 kg per hour in the best-case scenario. Further investigation is required to see whether this

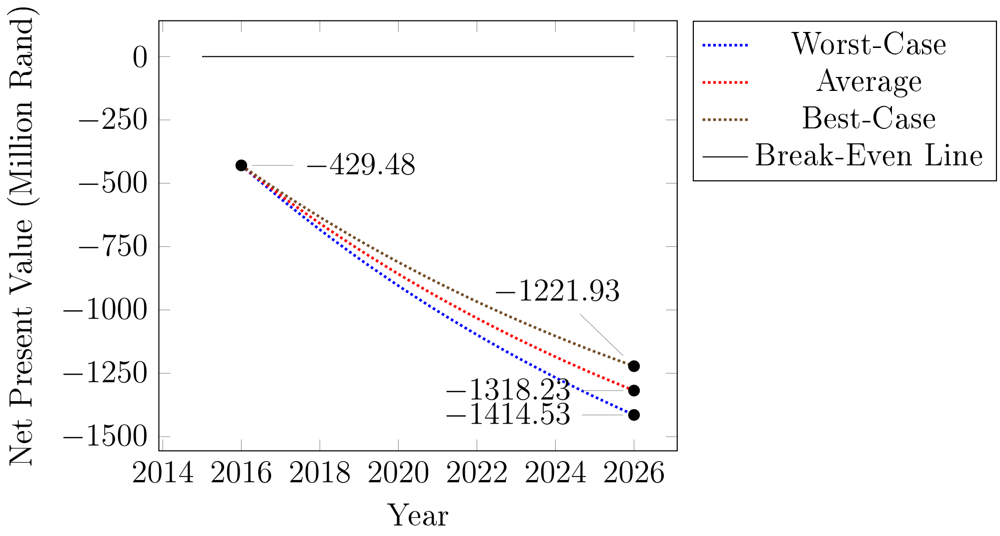


**Figure 6.14:** Scenario Analysis of PA CHM

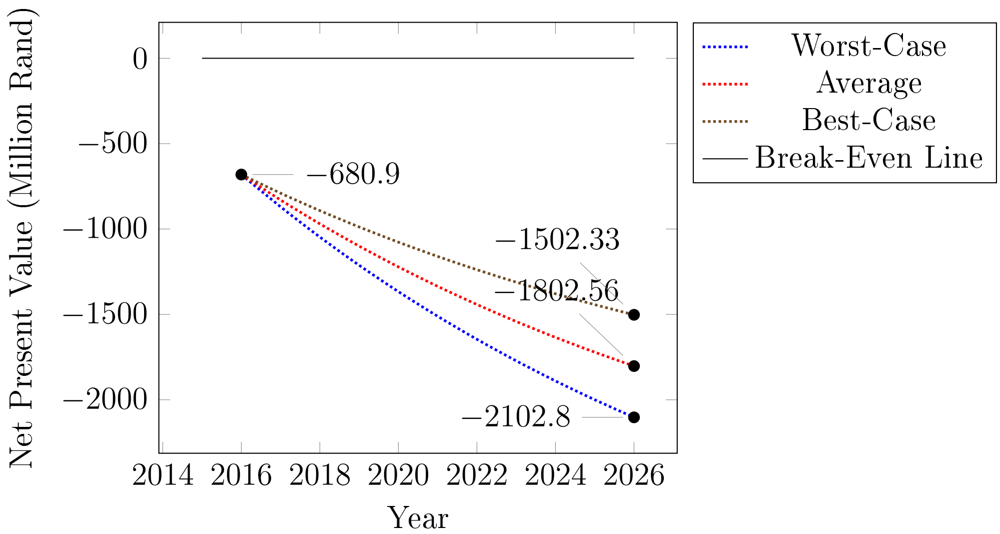


**Figure 6.15:** Scenario Analysis of Plate Production

method can operate at this pace.

In terms of break-even time, only the wash and briquette process and precision casting processes manage to break even within the analysis time period. The wash and briquette process breaks even after about 4 years for the average-case and 2 year for the best-case. This process does not break even within the analysis period for the worst-case. Precision casting breaks even after 4 years for the worst-case and 2 years for the average-case, while best-case scenario takes about 1 year. This serves as a rough discounted payback period (DPBP) calculation. While thermal degreasing and ferrotitanium production also have some scenarios with upward trends, from which the DPBP can be calculated, it is considered to be outside the scope of this project, as they only break even after the 10 year analysis period.

From the feasibility study, one can conclude with confidence that the best option for

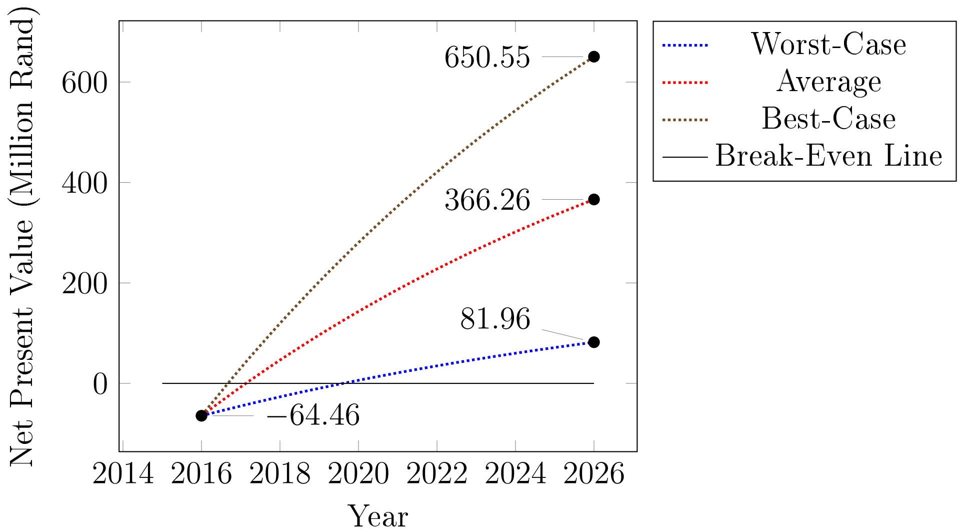


**Figure 6.16:** Scenario Analysis of Precision Casting

titanium recycling at present is precision vacuum casting. This option fits particularly well in a South African context as there is quality scrap available, but in small and unpredictable quantities. Precision vacuum casting allows one to use this high value scrap and produce near-net shape products, without the requirement of very large capital investment required by the larger scale recycling methods.

### 6.2.5 Discussion of Feasible Alternatives

This section will discuss the strengths, weaknesses, opportunities and threats of feasible recycling methods, as identified through the review of literature and discussion with industry experts. The feasibility study determined that only two of the eight recycling methods show promise of being feasible in South Africa at present. These are the washing and briquetting, and precision casting processes.

Washing scrap and compressing it into briquettes is the easiest method of adding value to scrap. It is also the cheapest in terms of initial investment costs, and locally sourced machinery can be used. Cheap, relatively uneducated labourers can be used, as no technical expertise is required. This method does not downgrade scrap to ferrograde and keeps the value thereof intact, however the benefit is not felt in South Africa. In terms of weaknesses, this process does not add much value to the scrap. It also does not contribute to creating a closed-loop titanium industry, as it requires foreign companies to melt the briquettes abroad, from where it will be bought back. There is a potential opportunity in learning from this methods and, once mastered, advancing to more complex recycling methods. Starting with the simplest process may be a good learning opportunity to get to know the titanium recycling market in greater detail, before investing in dedicated expensive equipment. Local titanium product manufacturers may also be excited by the prospect of a local company who is willing to buy their scrap at a higher price, without producing products which rival their own. Finally, there is an opportunity for "toll melting", a method by which one pays a company abroad, who has the desired melting capabilities, to melt the briquettes on one's behalf. By this method, cheaper mill products may be produced. In terms of threats, this process supplies companies abroad with a cheap, high quality source of scrap. Long term contracts, which local titanium component manufacturers may likely have with companies abroad, is a concern as they often sell their scrap back to primary fabricators, such as Timet, who provided them with mill products.

Precision casting provides a relatively cheap method of producing near-net shape products, avoiding expensive intermediate processes. Thus, the need for expensive forging equipment is eliminated. These near-net shape products are also of high value, when compared to the ingots and slabs produced by other melting processes. Some weaknesses of this process are that it is a challenging process, requiring much technical experience, and there may be a restricted market size for the products produced by precision casting. Furthermore, the method can only be used to produce non-critical, non-aerospace applications, as the feedstock scrap does not undergo the sufficient refining to remove HID's and HDI's. This also presents an opportunity for the local production of titanium golf club heads and jewellery. The major threat is that similar products, produced abroad, are of better quality and cheaper than those produced by local recycling.

## 6.3 Monte-Carlo Simulation Model

With the amount of scrap available at present in South Africa, it is clear that the most feasible alternatives are recycling titanium to briquettes and selling that abroad, and small scale precision titanium castings, based on the feasibility study detailed above. As the goal of this project is to find the best alternative for recycling, precision casting is investigated in more detail, by use of simulation. This allows one to introduce uncertainty into the feasibility model. The drawback of precision casting is the high capital investment cost required. The quote used in the feasibility study is for a furnace capable of melting components weighing up to 8kg. The furnace's high investment cost can be reduced by investigating smaller titanium investment casting furnaces. A detailed quote was obtained from Linn High Therm in Germany, who produce vacuum furnaces for small scale applications. The quote is for a furnace known as the TITANCAST-700-VAC, which is capable of melting titanium parts of 350g. It is specifically designed to melt titanium for jewellery applications.

Four simulations were run with 10 000 iterations each. The number of input variables is 733, each of which is simulated 10 000 times. In each simulation a different profit margin is taken and the effect thereof is observed. The three profit margins analysed are 130%, 140% and 150%, while the fourth simulation uses a set price per casting of R1000. These are the profit margins where the project becomes profitable on a more regular basis. The probability of being profitable is discussed and the sensitivity analysis, which shows which variables have the greatest effect on final NPV, is also discussed. The full summary of the simulations can also be seen in Appendix D.

The probability density functions for the first three simulations are seen in Figures 6.17, 6.19 and 6.21. It shows the minimum, maximum and mean values obtained with all iterations of the simulations on the right-hand side. Also shown are the standard deviations of the simulations and the amount of iterations, which is set to 10 000 for all three simulations. On the y-axis, the amount of iterations of the simulation out of 10 000 in a certain interval can be seen. The x-axis shows the net present value in million

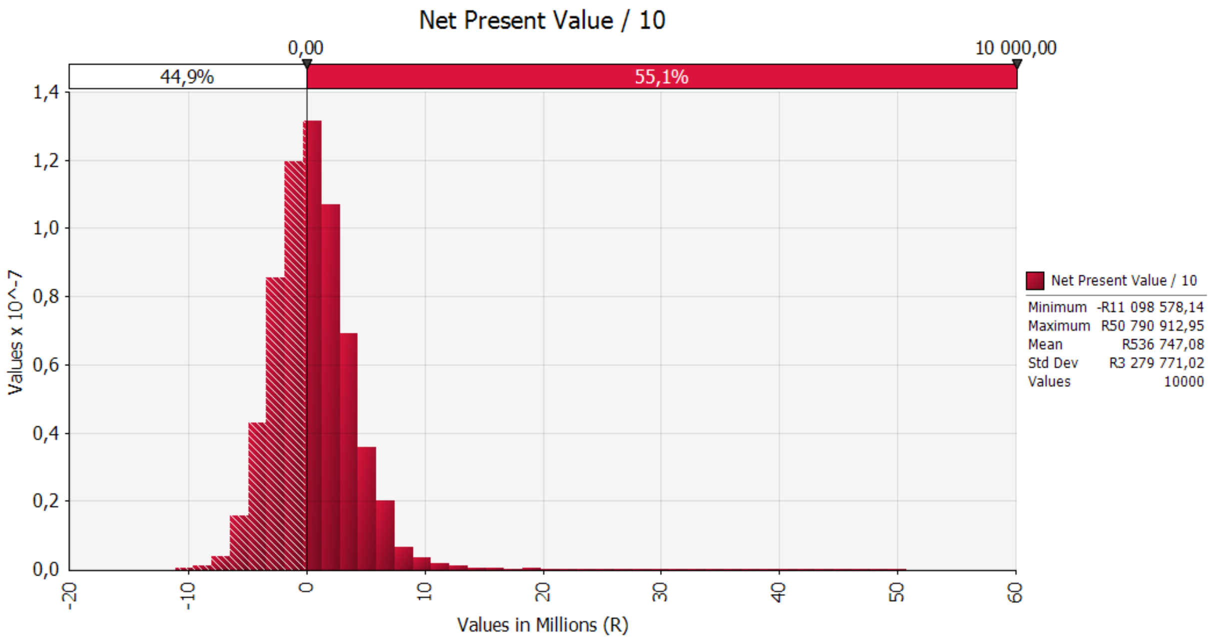


**Figure 6.17:** Probability Distribution Graph of Project with 130% Profit Margin

Rands after the ten year analysis period. At the top, the percentages are seen, showing the probability of having an NPV between a certain range. In this case the values are set to 0 and infinity to analyse the probability of having a positive NPV after ten years. Thus, it shows the probability of being feasible, based on the criteria set in the feasibility study.

In the first simulation the profit margin is taken as 130%. At this profit margin, the castings will sell for between R700 and R900 on average, but may change drastically if there is a year where very little scrap is available for processing. The castings will then need to sell for high amounts to cover the expenses of the process. As seen in Figure 6.17, the probability of having an NPV of more than 0 after ten years is 55.1%. At this rate, the project has a relatively large probability of being unsuccessful. The minimum NPV the project had with this simulation was about -R11 million, while the maximum was over R50 million. In Figure D.1 in Appendix D, the full summary of the simulation can be seen. The NPV has a 90% chance of having a value between -R4.31 million and R6.02 million, according to the full results.

The tornado plot seen in Figure 6.18 shows the sensitivity analysis of the input distributions. The tornado plot shows the input variables which have the highest influence on the output, in this case the NPV after ten years. Only the variables with the largest influence are shown and ranked. The bars show the effect the minimum and maximum value of the variable has on the NPV. This helps one to see where one should focus when attempting to reduce the price of the project and increase the probability of having a better outcome.

It is seen that the initial fixed capital investment has by far the largest influence on the final NPV. This is followed by the repo rate or inflation for the years 2017, 2020, 2019 and 2021. The efficiency of the process is ranked below this. The initial fixed capital investment's influence is so, that if it decreased by about R2 million, it will have the same

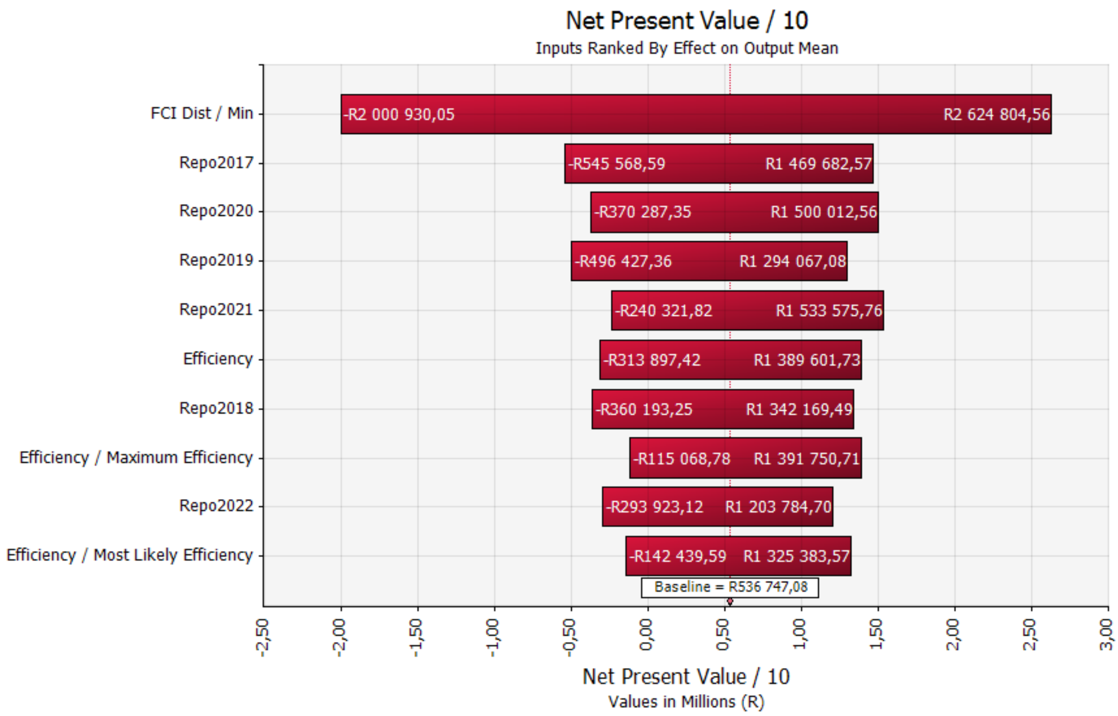


**Figure 6.18:** Tornado Plot of Project with 130% Profit Margin

effect on the NPV. This is because it is subtracted directly from the cash flow analysis and a negative NPV is taken.

At a 140% profit margin, the probability of being profitable increases to 87.3%, as can be seen in Figure 6.19. This means that there is still a 12.7% that the project will have a negative NPV after ten years. A minimum value of about -R6.7 million was achieved, while a maximum of R34.9 million was seen. The mean NPV was positive at R3.78 million. The full results of the simulation, as can be viewed in Figure D.2 in Appendix D, show that the simulation has a 90% chance of having an NPV of between -R1.51 million and R9.54 million.

A similar result is seen with the tornado plot with the 140% and 130% profit margins. This can be seen in Figure 6.20. Again, the initial fixed capital investment has the greatest influence. The interest rates for many years make a large difference, while the efficiency is again a significant factor. The historical scrap price, which is used to predict the hypothetical future price of scrap makes an appearance in this case. This shows that the price of scrap has a large effect on the final NPV as well.

At 150% profit, the chance of having a negative NPV after ten years is less than 1.5%, as can be seen in Figure 6.21. The smallest value an iteration of the simulation gave was about -R4 million. A maximum value of almost R38 million was obtained in one iteration. On average, the NPV was about R7.03 million after ten years. From the full results in Figure D.3, it can be seen that there is a 90% chance of having an NPV of between R1.52 million and R13.27 million. At a profit margin of 150% the chance of having a successful project is almost 99%.

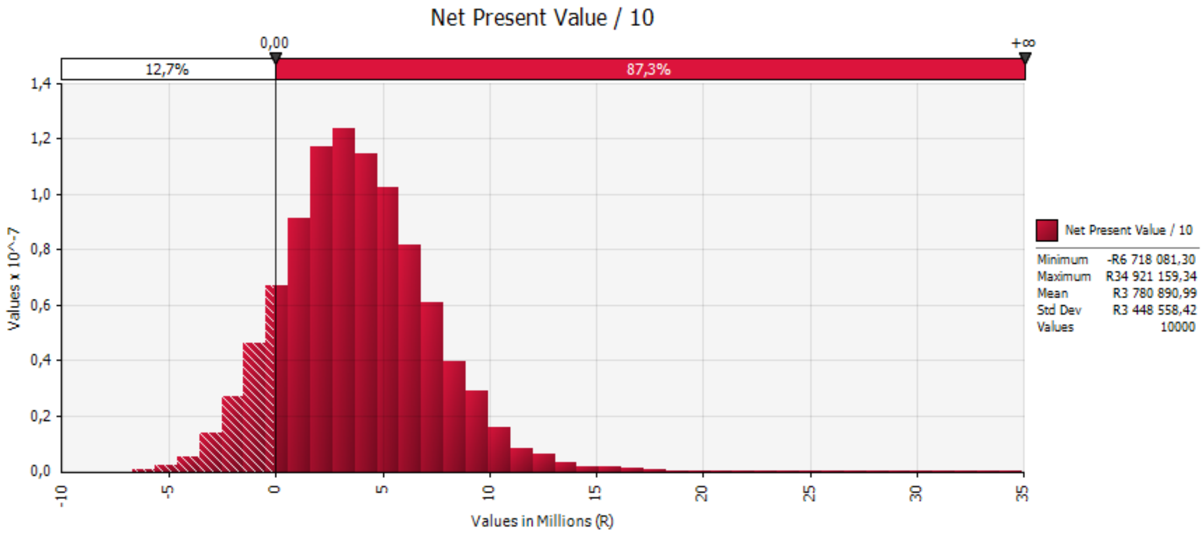


**Figure 6.19:** Probability Distribution Graph of Project with 140% Profit Margin

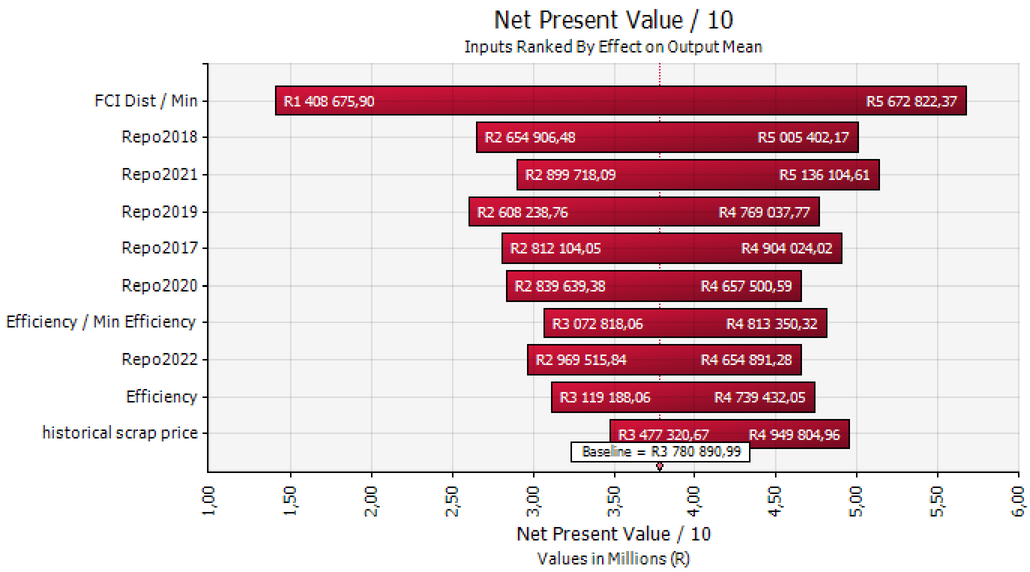


**Figure 6.20:** Tornado Plot of Project with 140% Profit Margin

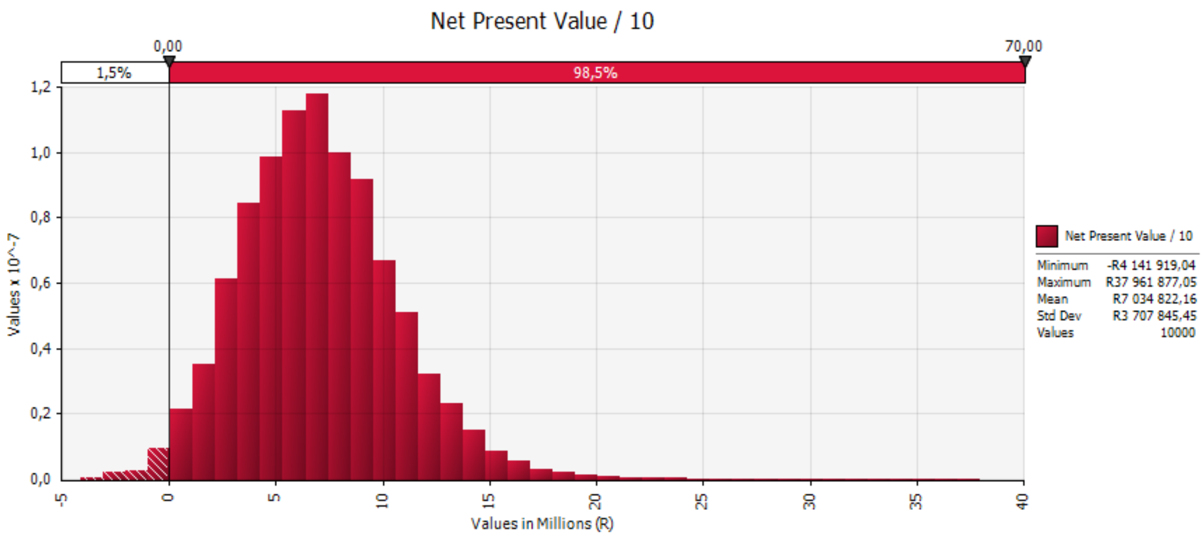


**Figure 6.21:** Probability Distribution Graph of Project with 150% Profit Margin

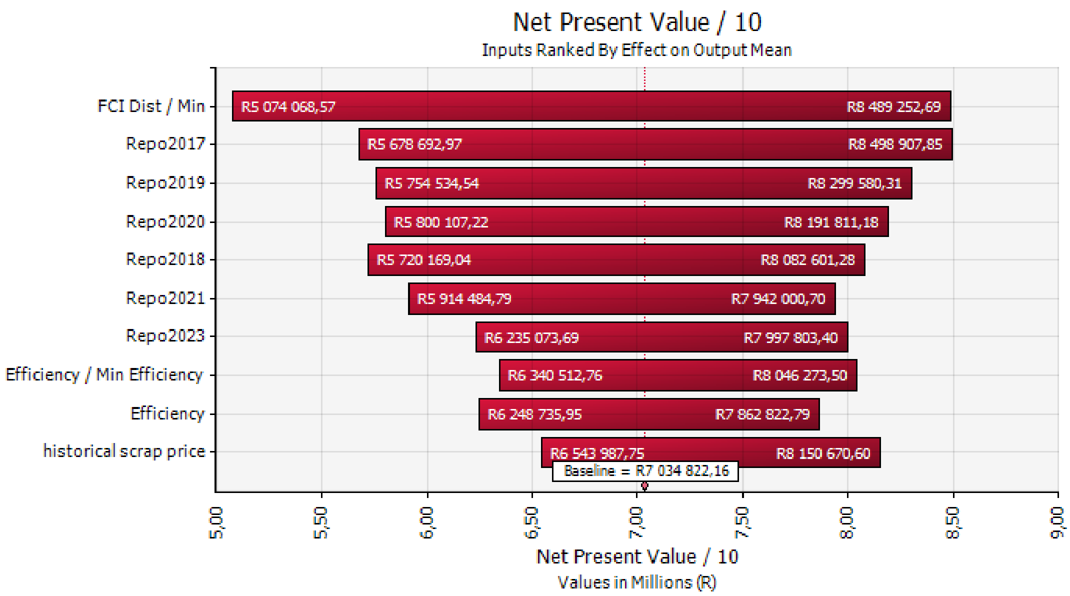


**Figure 6.22:** Tornado Plot of Project with 150% Profit Margin

The sensitivity analysis shows similar values again as seen in Figure 6.22, with the capital investment costs and interest rate having the largest influence again. The interest rate does seem to increase in influence as the profit margin increases. This is seen with a 140% profit margin as well. In this case, the high value interest rate in 2017 has a larger influence than that of the fixed capital investment value. This is most likely due to the fact that, as the cash flow increases, which occurs when the profit margin is increased, the bigger the amount that is discounted by the interest rate. The fixed capital investment is not affected by this, as it is already fixed at time equal to zero, and does not need to be discounted. This trend will most likely continue as the profit margin is increased and eventually, have a larger effect than the initial investment.

The sensitivity analysis of these three simulations leads one to conclude that the in-

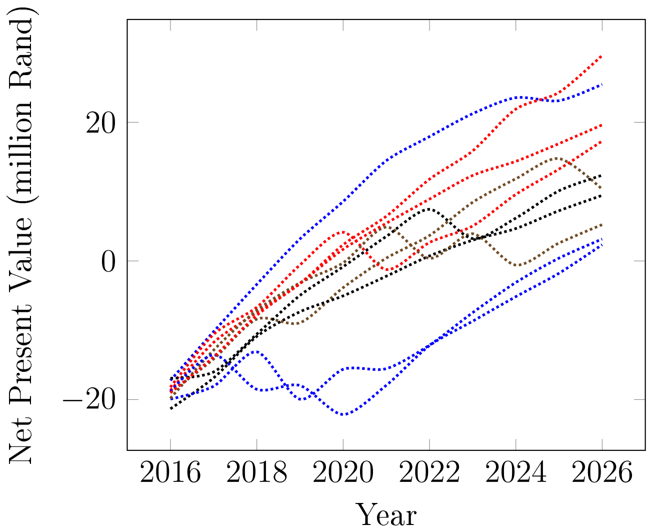


**Figure 6.23:** Sample of 11 Iterations with a Fixed Price per Casting

terest rate will be a major factor in the success of the project. While the fixed capital investment amount has the largest influence, its value is certain and cannot be avoided. The interest rate on the other hand has a high sensitivity and uncertainty, which makes it very influential when considering whether such a project should be attempted.

Because the fixed profit margin ensures that a loss can never occur, as it takes a markup on all expenses, one simulation is run with a fixed price per casting. The fixed profit margins negate the effect of some variables, while their influence can be observed when fixing the selling price. This will show how the model handles the years where there are outliers with regards to scrap shortages and other input variables. Figure 6.23 shows an example of eleven iterations being run using a selling price of R1000 per casting. From this image, the variability in simulation iterations can clearly be observed, while in a fixed profit margin simulation, all iterations will have positive trends. In the figure the variations introduced can be seen, as the NPV rises and falls considerably, based on market factors. This allows one to inspect a more realistic case, where the NPV does not always rise, as in the case where a fixed profit margin is used. The R1000 selling price is based on the average cast unit price at 150% profit margin and is a reasonable cost, compared to titanium jewellery on the market.

A summary of the results of the simulation are shown in Figure 6.24. It can be seen that the minimum value obtained is much smaller than that of when the profit margin is set to 150%, but the probability of this happening is very small. The shape of the probability distribution is also different to that when using a fixed profit margin. The distribution has a long left tail, showing that there are minute probabilities of having a low NPV. This is also seen in the percentage indicator at the top, with a 98.9% chance of having an NPV larger than zero. When a fixed profit margin is used the distribution appears more symmetrical, closer to a normal distribution. In the case where the price is fixed at R1000, the distribution is largely skewed to the left. The maximum amount is relatively similar to when a fixed profit margin was used at about R39 million, but the mean value is about R14 million more. From the full results in Figure D.4 in Appendix D, it can be seen that there is a 95% chance of having an NPV of between R7.85 million and

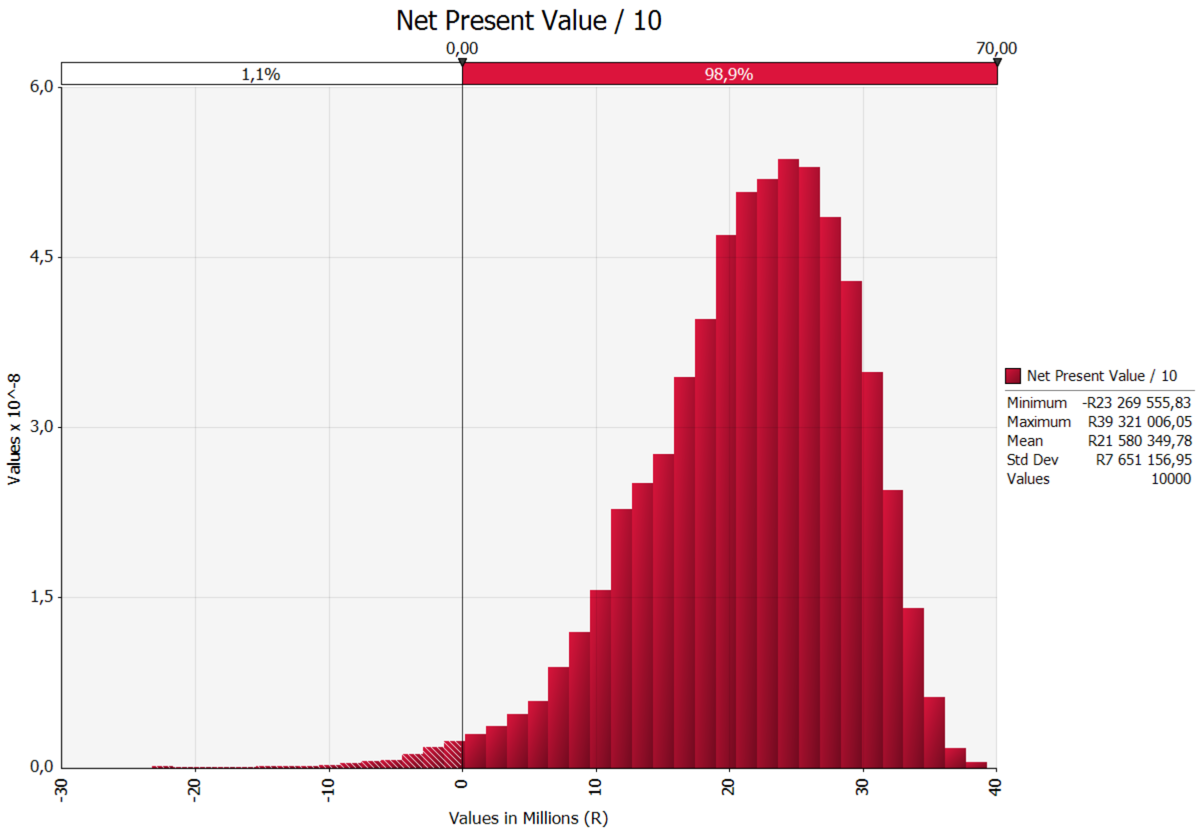


**Figure 6.24:** Probability Distribution Graph of Project with Selling Price set to R1000 per Cast

R32.33 million. This is also considerably improved when compared with a fixed margin.

The tornado plot also gives some interesting results, as seen in Figure 6.25. The fixed capital investment amount still has the largest influence on the results, but the amount of scrap available is seen as the largest secondary variable. It is seen that a low scrap amount equates to a reduction in the net present value, which is to be expected, as there will be less scrap to process. At a higher amount of scrap, however, it does not lead to increases in the NPV, as the throughput limit of the process is bounded. This addresses the problem initially identified with regards to scrap availability as a key issue in titanium recycling in South Africa.

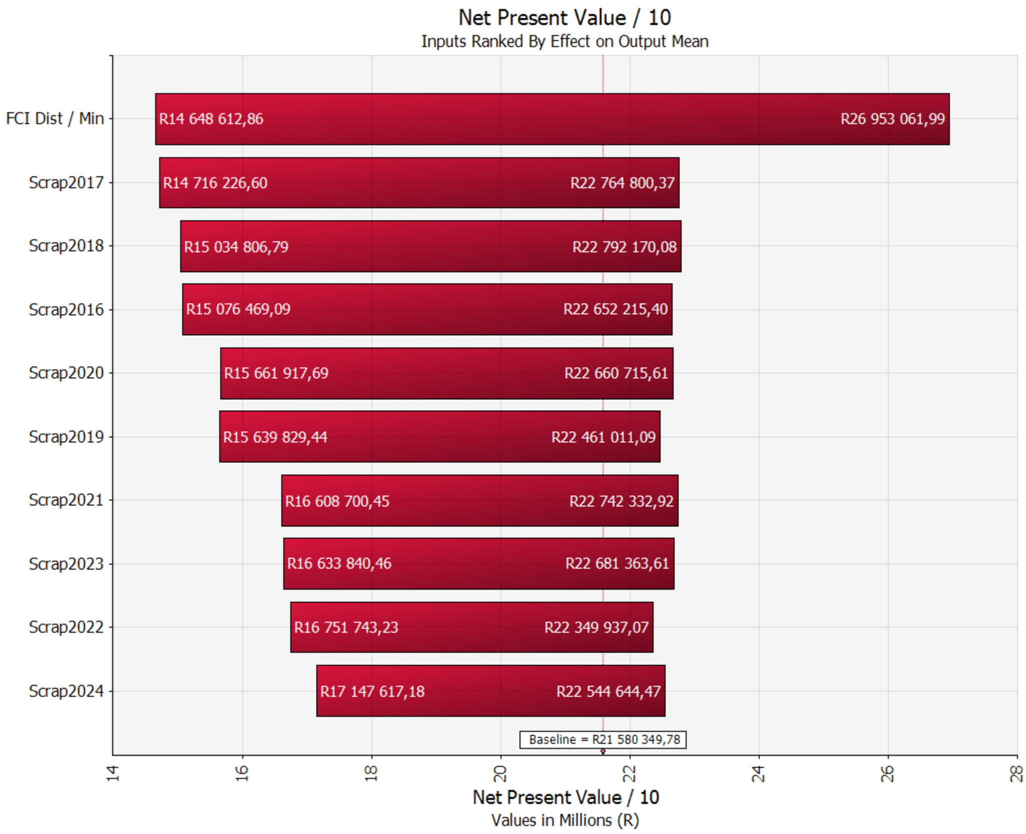


**Figure 6.25:** Tornado Plot of Project with Selling Price set to R1000 per Cast

# Chapter 7

# Conclusion

In this final chapter, the initial goals are restated and the results summarised. This is done with the goal to prove that this project was successful and all goals were achieved. A brief discussion is given of possible future work, which can be done using this thesis as groundwork.

## 7.1 Conclusion

This project set out to explore the possibilities of titanium recycling in South Africa. The initial aims were to research and map all possible methods of recycling titanium scrap and create a framework as well as cost models to assess the feasibility of these alternatives. The best recycling option, identified through the feasibility study, was to be modelled through simulation to create a business case for titanium recycling.

With the review of literature, the unique properties and challenges with regard to titanium, were identified. The production process of titanium was explained, as much recycling is done during primary processing. A review on the titanium market revealed prices of the metal in various forms, as well as possible international consumers, and local markets in the stainless steel industry. An overview of South Africa's current beneficiation projects showed the possibility of a scrap influx in the future.

Titanium recycling literature revealed the metal's relative recycling rate at present. The current state of titanium recycling in the United States was described and depicted in the form of a Sankey diagram. The unique challenges in the recycling of titanium that were identified, were of great importance and were ultimately introduced into the feasibility framework. Eight recycling processes were identified for analysis, namely precision casting, briquetting scrap, ferrotitanium production, thermal degreasing, vacuum-arc remelting, electron beam cold hearth metling, plasma arc cold hearth melting and mill product production.
A background study at Hansens Engineering (situated in Port Elizabeth) provided a platform to experience state-of-the-art recycling processes firsthand. The waste-to-resource strategies implemented gave experience and insight into waste-to-resource thinking, in addition to critical data requirements for the cost models.

A review on cost modelling techniques showed a factorial method of estimating the economic feasibility of a project. Through the use of Lang Factors, the cost models for all eight recycling methods were built. Measures of profitability, such as the net present value, indicated the probability of project being financially feasible. By use of a break-even analysis, a feasibility framework was compiled, which shows at which point each recycling method becomes feasible, in terms of scrap availability. The break-even analysis was also used in an illustrative case study, using benchmark components. This assisted in contextualising the break-even analysis' measurement in kilograms, to an amount of parts to be manufactured. Scenario analysis was also conducted by making use of best-case and worst-case estimates of the theoretical amount of scrap available for recycling in South Africa, at present.

The feasibility study showed that only two of the originally identified eight recycling processes proved financially feasible. Washing and briquetting scrap was the first which proved marginally feasible. With a break-even throughput of 69.1 tonnes per annum, it was slightly above the pessimistic (worst-case) scrap estimation, which was around 55 tonnes per annum. It was, however, well within the average and optimistic (best-case) estimates, which was 112.9 tonnes and 170.4 tonnes respectively. With a positive net present value of R14.58m and R35.81m for the average and best-case scrap availabilities, this recycling method can be very profitable if the hypothetical scrap availabilities prove accurate.

Precision casting was revealed to be the most profitable option for titanium recycling in South Africa. It was determined that the process breaks even at about 38.9 tonnes of scrap processed per annum. This is well below the worst-case scrap volume estimation. The net present value one can hope to achieve in the worst-case is over R80m after the ten-year analysis period, while exceeding R650m in the best case. It was determined that precision casting was by far the superior alternative in the current state of the South African titanium industry, and required an in-depth financial analysis.

Uncertainty was introduced into the precision casting model by the use of Monte-Carlo Simulation. The Lang Factor ranges, initially used in the feasibility model, were used as minimum and maximum values. The midpoint of the ranges was used as the most likely, and by use of these three values for each variable, a triangular distribution could be created for each input variable. Further uncertainty was modelled on factors such as exchange rates, inflation, utility costs, scrap availability, melt efficiency, and scrap price. The best fitting distributions were used in these cases, based on the AIC goodness of fit test. Four simulations were run and it was found that, by using a profit margin of 150% or a fixed selling price of R1000 per casting, one can be almost 99% certain of having a positive net present value after ten years. At a 130% and a 140% fixed profit margin, the probabilities of having a positive NPV were 55.1% and 87.3%, respectively.

All the initial aims of this project were achieved. An in-depth literature review identified and mapped all methods capable of recycling titanium. This was then utilised in the composition of the feasibility framework. Through the feasibility study, precision casting was identified as the best option for recycling of the metal. A business case was created through a Monte-Carlo simulation model, which shows the overwhelming probability of success for a recycling endeavour of this type.

## 7.2 Future Work and Outlook

It is suggested that physical experiments be conducted in future work, to build on this theoretical knowledge with practical studies. As this research suggests, precision vacuum casting would be the preferred option for conducting initial experiments. Experiments with emerging technologies, such as HDH titanium powder production from scrap, can be performed as an alternative to large-scale melting equipment. Other options to conduct recycling experiments include, recycling through severe plastic deformation (SPD) or replication of the IME process at Stellenbosch University.

The HDH method presents a particularly suitable recycling option, since the powder produced from the process can possibly be used in selective laser melting (SLM) projects at Stellenbosch University. Further encouraging signs for this method are that experiments by local authors, Chhiba (2012) and Goso and Kale (2011), have successfully produced titanium powder by use of the HDH method. The possibility of remelting titanium scrap with CSIR powder instead of raw sponge can also be explored. This may give a feasible method of producing local titanium mill products.

As previously stated, this study conducts a preliminary feasibility study. If commercial implementation of a recycling process is planned, it is suggested that a Class 1 estimate be done for improved accuracy, as a feasibility study estimations are expected to rise up to 72% over budget or fall 48% under budget. A Class 1 estimate will not be over budget by more than 6% or under budget by less than 4%.

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# Appendices

# Appendix A

# Feasibility Model Inputs and Calculations

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Throughput | 34,68793951 | 27,84551707 | 28,34658258 | 42,77040663 | kg/hr |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 1 | 1 | 2 | 2 | Shifts |
| Theoretical Output | 69098,37551 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 35 | 35 | 35 | 35 | R/hr |
| Nr Workers | 1 | 1 | 1 | 1 | Workers |
| Yearly Wage | 69720 | 69720 | 139440 | 139440 | |
| Waste Treatment Cost | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 660,8 | 660,8 | 1321,6 | 1321,6 | kWh/day |

**Figure A.1:** Process Inputs for Wash and Briquette Process

| Capital Investment | Lang Factor | | | Cost |
|---|---|---|---|---|
| Equipment | 1 | | | R 2 950 000,00 |
| Erection of items | 0,11 | | | R 324 500,00 |
| Structural and Buildings | 0,26 | | | R 767 000,00 |
| Civils | 0,17 | | | R 501 500,00 |
| Piping & Ducting | 0,14 | | | R 413 000,00 |
| Electrical | 0,26 | | | R 767 000,00 |
| Instruments | 0,1 | | | R 295 000,00 |
| | | | | R 6 018 000,00 |
| | | | | |
| Installed Plant | | | | |
| GST | 0,13 | | | R 782 340,00 |
| Site Prep | 0,05 | | | R 340 017,00 |
| Construction Management | 0,15 | | | R 1 071 053,55 |
| Contingency | 0,15 | | | R 1 231 711,58 |
| | | | | R 3 425 122,13 |
| | | | | |
| FCI | | | | R 9 443 122,13 |
| | | | | |
| Initial Loan | | | | 9443122,13 |
| Annual Interest Rate | | | | 10,5% |
| Years | | | | 10 |
| Total Compounding Periods | | | | 120 |
| Compounding Periods Per Year | | | | 12 |
| Effective Annual Interest Rate | | | | 11,02035% |
| Future Value | | | | 26862184,91 |
| Monthly Installment | | | | R 127 420,77 |
| Yearly Total | | | | R 1 529 049,19 |
| | | | | |
| Discounting Factor | | | | 7% |
| | | | | |
| Depreciation | | | | |
| Fixed Capital Investment | 9443122,133 | | | |
| Salvage Value | 0 | | | |
| Life of Equipment | 10 | | | |

**Figure A.2:** Capital Investment Cost Input and Calculations for Wash and Briquette Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 1 105 574,01 |
| Waste Treatment | | | | R 112 630,35 |
| Utilities | | | | R 103 659,70 |
| Operating Labour | | | | R 69 720,00 |
| Direct Supervisory and Clerica | 0,1 | 0,25 | 0,175 | R 12 201,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 566 587,33 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 84 988,10 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 10 458,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 133 809,08 |
| DMC | | | | R 2 199 627,56 |
| | | | | |
| Depreciation | | | 0,1 | R 944 312,21 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 302 179,91 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 347 273,00 |
| FMC | | | | R 1 593 765,12 |
| | | | | |
| Administration | | | 0,15 | R 97 276,25 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 490 633,28 |
| Research and Development | | | 0,05 | R 223 015,13 |
| GE | | | | R 810 924,66 |
| | | | | |
| | | | | |
| COM | | | | R 4 460 302,59 |
| COM_d | | | | R 3 515 990,37 |
| | | | | |
| Income | | | | R 6 545 151,68 |

**Figure A.3:** Cost of Manufacturing Calculations for Wash and Briquette Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 887 492,32 |
| Waste Treatment | | | | R 90 413,28 |
| Utilities | | | | R 103 659,70 |
| Operating Labour | | | | R 69 720,00 |
| Direct Supervisory and Clerica | 0,1 | 0,25 | 0,175 | R 12 201,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 566 587,33 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 84 988,10 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 10 458,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 124 942,05 |
| DMC | | | | R 1 950 461,78 |
| | | | | |
| Depreciation | | | 0,1 | R 944 312,21 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 302 179,91 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 347 273,00 |
| FMC | | | | R 1 593 765,12 |
| | | | | |
| Administration | | | 0,15 | R 97 276,25 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 458 120,86 |
| Research and Development | | | 0,05 | R 208 236,76 |
| GE | | | | R 763 633,87 |
| | | | | |
| | | | | |
| COM | | | | R 4 164 735,11 |
| COM_d | | | | R 3 220 422,90 |
| | | | | |
| Income | | | | R 5 254 077,80 |

**Figure A.4:** Cost of Manufacturing Calculations for Wash and Briquette Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 1 806 924,56 |
| Waste Treatment | | | | R 184 080,44 |
| Utilities | | | | R 207 319,39 |
| Operating Labour | | | | R 139 440,00 |
| Direct Supervisory and Clerica | 0,1 | 0,25 | 0,175 | R 24 402,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 566 587,33 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 84 988,10 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 20 916,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 171 860,53 |
| DMC | | | | R 3 206 518,35 |
| | | | | |
| Depreciation | | | 0,1 | R 944 312,21 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 302 179,91 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 354 593,60 |
| FMC | | | | R 1 601 085,72 |
| | | | | |
| Administration | | | 0,15 | R 109 564,40 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 630 155,28 |
| Research and Development | | | 0,05 | R 286 434,22 |
| GE | | | | R 1 026 153,90 |
| | | | | |
| | | | | |
| COM | | | | R 5 728 684,40 |
| COM_d | | | | R 4 784 372,19 |
| | | | | |
| Income | | | | R 10 697 244,36 |

**Figure A.5:** Cost of Manufacturing Calculations for Wash and Briquette Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 2 726 356,80 |
| Waste Treatment | | | | R 277 747,60 |
| Utilities | | | | R 207 319,39 |
| Operating Labour | | | | R 139 440,00 |
| Direct Supervisory and Clerica | 0,1 | 0,25 | 0,175 | R 24 402,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 566 587,33 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 84 988,10 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 20 916,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 209 243,90 |
| DMC | | | | R 4 257 001,12 |
| | | | | |
| Depreciation | | | 0,1 | R 944 312,21 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 302 179,91 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 354 593,60 |
| FMC | | | | R 1 601 085,72 |
| | | | | |
| Administration | | | 0,15 | R 109 564,40 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 767 227,63 |
| Research and Development | | | 0,05 | R 348 739,83 |
| GE | | | | R 1 225 531,86 |
| | | | | |
| | | | | |
| COM | | | | R 6 974 796,66 |
| COM_d | | | | R 6 030 484,45 |
| | | | | |
| Income | | | | R 16 140 410,92 |

**Figure A.6:** Cost of Manufacturing Calculations for Wash and Briquette Process Best-Case

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Throughput | 95,23948776 | 27,84551707 | 56,69316516 | 85,54081325 | kg/hr |
| Actual Cap | 12550,2008 | 12550,2008 | 12550,2008 | 12550,2008 | |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 1 | 1 | 1 | 1 | Shifts |
| Theoretical Output | 189717,0596 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 35 | 35 | 35 | 35 | R/hr |
| Nr Workers | 3 | 3 | 3 | 3 | Workers |
| Yearly Wage | 209160 | 209160 | 209160 | 209160 | |
| Waste Treatment Co | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 180 | 180 | 180 | 180 | kWh/tonne |
| Gas Use | 374 | 374 | 374 | 374 | m^3/tonne |

**Figure A.7:** Process Inputs for Thermal Degreasing Process

| Capital Investment | Lang Factor | Cost |
|---|---|---|
| Equipment | 1 | R 22 716 046,21 |
| Adjusting to Smallest International Capacity | 401,6064257 | R 2 880 200,56 |
| Erection of items | 0,11 | R 316 822,06 |
| Structural and Buildings | 0,26 | R 748 852,15 |
| Civils | 0,17 | R 489 634,10 |
| Piping & Ducting | 0,14 | R 403 228,08 |
| Electrical | 0,26 | R 748 852,15 |
| Instruments | 0,1 | R 288 020,06 |
| | | R 5 875 609,14 |
| | | |
| Installed Plant | | |
| GST | 0,13 | R 763 829,19 |
| Site Prep | 0,05 | R 331 971,92 |
| Construction Management | 0,15 | R 1 045 711,54 |
| Contingency | 0,15 | R 1 202 568,27 |
| | | R 3 344 080,91 |
| | | |
| FCI | | R 9 219 690,05 |
| | | |
| Initial Loan | | 9219690,05 |
| Annual Interest Rate | | 10,5% |
| Years | | 10 |
| Total Compounding Periods | | 120 |
| Compounding Periods Per Year | | 12 |
| Effective Annual Interest Rate | | 11,02035% |
| Future Value | | 26226603,4 |
| Monthly Installment | | R 124 405,88 |
| Yearly Total | | R 1 492 870,62 |
| | | |
| Discounting Factor | | 7% |
| | | |
| Depreciation | | |
| Fixed Capital Investment | 9219690,053 | |
| Salvage Value | 0 | |
| Life of Equipment | 10 | |

**Figure A.8:** Capital Investment Cost Input and Calculations for Thermal Degreasing-Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 121 418,92 |
| Waste Treatment | | | | R 309 238,81 |
| Utilities | | | | R 21 513,91 |
| Operating Labour | | | | R 209 160,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 36 603,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 553 181,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 82 977,21 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 31 374,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 111 260,73 |
| DMC | | | | R 1 476 727,99 |
| | | | | |
| Depreciation | | | 0,1 | R 921 969,01 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 295 030,08 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 353 870,64 |
| FMC | | | | R 1 570 869,73 |
| | | | | |
| Administration | | | 0,15 | R 119 841,66 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 407 956,02 |
| Research and Development | | | 0,05 | R 185 434,56 |
| GE | | | | R 713 232,24 |
| | | | | |
| COM | | | | R 3 708 691,13 |
| COM_d | | | | R 2 786 722,13 |
| | | | | |
| Income | | | | R 5 744 210,97 |

**Figure A.9:** Cost of Manufacturing Calculations for Thermal Degreasing Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 35 499,69 |
| Waste Treatment | | | | R 90 413,28 |
| Utilities | | | | R 6 290,10 |
| Operating Labour | | | | R 209 160,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 36 603,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 553 181,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 82 977,21 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 31 374,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 99 453,89 |
| DMC | | | | R 1 144 952,58 |
| | | | | |
| Depreciation | | | 0,1 | R 921 969,01 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 295 030,08 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 353 870,64 |
| FMC | | | | R 1 570 869,73 |
| | | | | |
| Administration | | | 0,15 | R 119 841,66 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 364 664,28 |
| Research and Development | | | 0,05 | R 165 756,49 |
| GE | | | | R 650 262,43 |
| | | | | |
| COM | | | | R 3 315 129,80 |
| COM_d | | | | R 2 393 160,79 |
| | | | | |
| Income | | | | R 1 679 455,95 |

**Figure A.10:** Cost of Manufacturing Calculations for Thermal Degreasing Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 72 276,98 |
| Waste Treatment | | | | R 184 080,44 |
| Utilities | | | | R 12 806,58 |
| Operating Labour | | | | R 209 160,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 36 603,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 553 181,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 82 977,21 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 31 374,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 104 507,75 |
| DMC | | | | R 1 286 967,37 |
| | | | | |
| Depreciation | | | 0,1 | R 921 969,01 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 295 030,08 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 353 870,64 |
| FMC | | | | R 1 570 869,73 |
| | | | | |
| Administration | | | 0,15 | R 119 841,66 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 383 195,09 |
| Research and Development | | | 0,05 | R 174 179,59 |
| GE | | | | R 677 216,34 |
| | | | | |
| COM | | | | R 3 483 591,73 |
| COM_d | | | | R 2 561 622,73 |
| | | | | |
| Income | | | | R 3 419 353,77 |

**Figure A.11:** Cost of Manufacturing Calculations for Thermal Degreasing Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 109 054,27 |
| Waste Treatment | | | | R 277 747,60 |
| Utilities | | | | R 19 323,05 |
| Operating Labour | | | | R 209 160,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 36 603,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 553 181,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 82 977,21 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 31 374,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 109 561,61 |
| DMC | | | | R 1 428 982,15 |
| | | | | |
| Depreciation | | | 0,1 | R 921 969,01 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 295 030,08 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 353 870,64 |
| FMC | | | | R 1 570 869,73 |
| | | | | |
| Administration | | | 0,15 | R 119 841,66 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 401 725,90 |
| Research and Development | | | 0,05 | R 182 602,68 |
| GE | | | | R 704 170,25 |
| | | | | |
| COM | | | | R 3 652 053,67 |
| COM_d | | | | R 2 730 084,67 |
| | | | | |
| Income | | | | R 5 159 251,58 |

**Figure A.12:** Cost of Manufacturing Calculations for Thermal Degreasing Process Best-Case

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Throughput | 48,63440779 | 27,84551707 | 28,34658258 | 42,77040663 | kg/hr |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 2 | 1 | 2 | 2 | Shifts |
| Theoretical Outpu | 193759,4806 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 35 | 35 | 35 | 35 | R/hr |
| Nr Workers | 3 | 3 | 3 | 3 | Workers |
| Yearly Wage | 418320 | 209160 | 418320 | 418320 | |
| Waste Treatment | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 6353,6 | 3176,8 | 6353,6 | 6353,6 | kWh/day |

**Figure A.13:** Process Inputs for Ferrotitanium Process

| | | | | |
|---|---|---|---|---|
| Capital Investment | Lang Factor | | | Cost |
| Equipment | 1 | | | R 6 387 500,00 |
| Erection of items | 0,11 | | | R 702 625,00 |
| Structural and Buildings | 0,26 | | | R 1 660 750,00 |
| Civils | 0,17 | | | R 1 085 875,00 |
| Piping & Ducting | 0,14 | | | R 894 250,00 |
| Electrical | 0,26 | | | R 1 660 750,00 |
| Instruments | 0,1 | | | R 638 750,00 |
| | | | | R 13 030 500,00 |
| | | | | |
| Installed Plant | | 3,20105835 | R 20 446 760,21 | |
| GST | 0,13 | | | R 1 693 965,00 |
| Site Prep | 0,05 | | | R 736 223,25 |
| Construction Management | 0,15 | | | R 2 319 103,24 |
| Contingency | 0,15 | | | R 2 666 968,72 |
| | | | | R 7 416 260,21 |
| | | | | |
| FCI | | | | R 20 446 760,21 |
| | | | | |
| Initial Loan | | | | 20446760,21 |
| Annual Interest Rate | | | | 10,5% |
| Years | | | | 10 |
| Total Compounding Periods | | | | 120 |
| Compounding Periods Per Year | | | | 12 |
| Effective Annual Interest Rate | | | | 11,02035% |
| Future Value | | | | 58163459,7 |
| Monthly Installment | | | | R 275 898,35 |
| Yearly Total | | | | R 3 310 780,23 |
| | | | | |
| Discounting Factor | | | | 7% |
| | | | | |
| Depreciation | | | | |
| Fixed Capital Investment | 20446760,21 | | | |
| Salvage Value | 0 | | | |
| Life of Equipment | 10 | | | |

**Figure A.14:** Capital Investment Cost Input and Calculations for Ferrotitanium Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 2 337 223,73 |
| Waste Treatment | | | | R 315 827,95 |
| Utilities | | | | R 996 689,23 |
| Operating Labour | | | | R 418 320,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 73 206,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 1 226 805,61 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 184 020,84 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 62 748,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 340 688,63 |
| DMC | | | | R 5 955 530,01 |
| | | | | |
| Depreciation | | | 0,1 | R 2 044 676,02 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 654 296,33 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 780 006,97 |
| FMC | | | | R 3 478 979,32 |
| | | | | |
| Administration | | | 0,15 | R 257 749,74 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 1 249 191,66 |
| Research and Development | | | 0,05 | R 567 814,39 |
| GE | | | | R 2 074 755,79 |
| | | | | |
| COM | | | | R 11 356 287,79 |
| COM_d | | | | R 9 311 611,77 |
| | | | | |
| Income | | | | R 15 870 516,13 |

**Figure A.15:** Cost of Manufacturing Calculations for Ferrotitanium Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 669 086,01 |
| Waste Treatment | | | | R 90 413,28 |
| Utilities | | | | R 498 344,62 |
| Operating Labour | | | | R 209 160,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 36 603,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 1 226 805,61 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 184 020,84 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 31 374,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 235 297,43 |
| DMC | | | | R 3 181 104,79 |
| | | | | |
| Depreciation | | | 0,1 | R 2 044 676,02 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 654 296,33 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 758 045,17 |
| FMC | | | | R 3 457 017,52 |
| | | | | |
| Administration | | | 0,15 | R 220 885,29 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 862 757,24 |
| Research and Development | | | 0,05 | R 392 162,38 |
| GE | | | | R 1 475 804,92 |
| | | | | |
| COM | | | | R 7 843 247,66 |
| COM_d | | | | R 5 798 571,64 |
| | | | | |
| Income | | | | R 4 543 313,55 |

**Figure A.16:** Cost of Manufacturing Calculations for Ferrotitanium Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 1 362 251,72 |
| Waste Treatment | | | | R 184 080,44 |
| Utilities | | | | R 996 689,23 |
| Operating Labour | | | | R 418 320,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 73 206,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 1 226 805,61 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 184 020,84 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 62 748,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 299 850,68 |
| DMC | | | | R 4 807 972,53 |
| | | | | |
| Depreciation | | | 0,1 | R 2 044 676,02 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 654 296,33 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 780 006,97 |
| FMC | | | | R 3 478 979,32 |
| | | | | |
| Administration | | | 0,15 | R 257 749,74 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 1 099 452,50 |
| Research and Development | | | 0,05 | R 499 751,14 |
| GE | | | | R 1 856 953,39 |
| | | | | |
| | | | | |
| COM | | | | R 9 995 022,77 |
| COM_d | | | | R 7 950 346,75 |
| | | | | |
| Income | | | | R 9 250 136,20 |

**Figure A.17:** Cost of Manufacturing Calculations for Ferrotitanium Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 2 055 417,43 |
| Waste Treatment | | | | R 277 747,60 |
| Utilities | | | | R 996 689,23 |
| Operating Labour | | | | R 418 320,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 73 206,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 1 226 805,61 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 184 020,84 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 62 748,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 328 884,82 |
| DMC | | | | R 5 623 839,53 |
| | | | | |
| Depreciation | | | 0,1 | R 2 044 676,02 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 654 296,33 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 780 006,97 |
| FMC | | | | R 3 478 979,32 |
| | | | | |
| Administration | | | 0,15 | R 257 749,74 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 1 205 910,99 |
| Research and Development | | | 0,05 | R 548 141,36 |
| GE | | | | R 2 011 802,09 |
| | | | | |
| | | | | |
| COM | | | | R 10 962 827,20 |
| COM_d | | | | R 8 918 151,18 |
| | | | | |
| Income | | | | R 13 956 958,85 |

**Figure A.18:** Cost of Manufacturing Calculations for Ferrotitanium Process Best-Case

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Max Real Throughput | 286,6253511 | 27,84551707 | 56,69316516 | 85,54081325 | kg/hr |
| Actual Max Cap | 200 | 200 | 200 | 200 | |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 3 | 1 | 1 | 1 | Shifts |
| Theoretical Output | 1712873,098 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 195,8333333 | 195,8333333 | 195,8333333 | 195,8333333 | R/hr |
| Nr Workers | 6 | 6 | 6 | 6 | Workers |
| Yearly Wage | 7021800 | 2340600 | 2340600 | 2340600 | |
| Waste Treatment Cost | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 2400 | 800 | 800 | 800 | kWh/day |

**Figure A.19:** Process Inputs for VAR Process

| Capital Investment | Lang Factor | | | Cost |
|---|---|---|---|---|
| Equipment | 1 | | | R 217 035 454,93 |
| Adjusting to Smallest International Capacity | 100,4016064 | | | R 143 534 759,38 |
| Erection of items | 0,11 | | | R 15 788 823,53 |
| Structural and Buildings | 0,26 | | | R 37 319 037,44 |
| Civils | 0,17 | | | R 24 400 909,09 |
| Piping & Ducting | 0,14 | | | R 20 094 866,31 |
| Electrical | 0,26 | | | R 37 319 037,44 |
| Instruments | 0,1 | | | R 14 353 475,94 |
| | | | | R 292 810 909,13 |
| | | | | |
| Installed Plant | | | | |
| GST | 0,13 | | | R 38 065 418,19 |
| Site Prep | 0,05 | | | R 16 543 816,37 |
| Construction Management | 0,15 | | | R 52 113 021,55 |
| Contingency | 0,15 | | | R 59 929 974,78 |
| | | | | R 166 652 230,89 |
| | | | | |
| FCI | | | | R 459 463 140,02 |
| | | | | |
| Initial Loan | | | | 459463140,02 |
| Annual Interest Rate | | | | 10,5% |
| Years | | | | 10 |
| Total Compounding Periods | | | | 120 |
| Compounding Periods Per Year | | | | 12 |
| Effective Annual Interest Rate | | | | 11,02035% |
| Future Value | | | | 1307002457 |
| Monthly Installment | | | | R 6 199 765,73 |
| Yearly Total | | | | R 74 397 188,78 |
| | | | | |
| Discounting Factor | | | | 7% |
| | | | | |
| Depreciation | | | | |
| Fixed Capital Investment | R 459 463 140,02 | | | |
| Salvage Value | 0 | | | |
| Life of Equipment | 10 | | | |

**Figure A.20:** Capital Investment Cost Input and Calculations for VAR Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 158 512 131,30 |
| Waste Treatment | | | | R 697 995,79 |
| Utilities | | | | R 597 600,00 |
| Operating Labour | | | | R 7 021 800,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 1 228 815,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 27 567 788,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 4 135 168,26 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 1 053 270,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 10 331 480,93 |
| DMC | | | | R 211 146 049,67 |
| | | | | |
| Depreciation | | | 0,1 | R 45 946 314,00 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 14 702 820,48 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 17 277 962,04 |
| FMC | | | | R 77 927 096,52 |
| | | | | |
| Administration | | | 0,15 | R 5 372 760,51 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 37 882 096,73 |
| Research and Development | | | 0,05 | R 17 219 134,88 |
| GE | | | | R 60 473 992,11 |
| | | | | |
| COM | | | | R 344 382 697,52 |
| COM_d | | | | R 298 436 383,52 |
| | | | | |
| Income | | | | R 445 822 803,62 |

**Figure A.21:** Cost of Manufacturing Calculations for VAR Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 5 133 126,15 |
| Waste Treatment | | | | R 22 603,32 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 27 567 788,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 4 135 168,26 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 4 248 782,41 |
| DMC | | | | R 44 407 963,55 |
| | | | | |
| Depreciation | | | 0,1 | R 45 946 314,00 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 14 702 820,48 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 16 786 436,04 |
| FMC | | | | R 77 435 570,52 |
| | | | | |
| Administration | | | 0,15 | R 4 547 699,01 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 15 578 868,85 |
| Research and Development | | | 0,05 | R 7 081 304,02 |
| GE | | | | R 27 207 871,88 |
| | | | | |
| COM | | | | R 141 626 080,46 |
| COM_d | | | | R 95 679 766,45 |
| | | | | |
| Income | | | | R 14 437 158,05 |

**Figure A.22:** Cost of Manufacturing Calculations for VAR Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 10 450 988,15 |
| Waste Treatment | | | | R 46 020,11 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 27 567 788,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 4 135 168,26 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 4 445 875,60 |
| DMC | | | | R 49 946 335,52 |
| | | | | |
| Depreciation | | | 0,1 | R 45 946 314,00 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 14 702 820,48 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 16 786 436,04 |
| FMC | | | | R 77 435 570,52 |
| | | | | |
| Administration | | | 0,15 | R 4 547 699,01 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 16 301 543,87 |
| Research and Development | | | 0,05 | R 7 409 792,67 |
| GE | | | | R 28 259 035,55 |
| | | | | |
| COM | | | | R 148 195 853,36 |
| COM_d | | | | R 102 249 539,36 |
| | | | | |
| Income | | | | R 29 393 894,32 |

**Figure A.23:** Cost of Manufacturing Calculations for VAR Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 15 768 850,14 |
| Waste Treatment | | | | R 69 436,90 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 27 567 788,40 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 4 135 168,26 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 4 642 968,79 |
| DMC | | | | R 55 484 707,49 |
| | | | | |
| Depreciation | | | 0,1 | R 45 946 314,00 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 14 702 820,48 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 16 786 436,04 |
| FMC | | | | R 77 435 570,52 |
| | | | | |
| Administration | | | 0,15 | R 4 547 699,01 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 17 024 218,89 |
| Research and Development | | | 0,05 | R 7 738 281,31 |
| GE | | | | R 29 310 199,21 |
| | | | | |
| COM | | | | R 154 765 626,26 |
| COM_d | | | | R 108 819 312,26 |
| | | | | |
| Income | | | | R 44 350 630,58 |

**Figure A.24:** Cost of Manufacturing Calculations for VAR Process Best-Case

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Throughput | 120,2924075 | 27,84551707 | 56,69316516 | 85,54081325 | kg/hr |
| Actual Max Cap | 700 | 700 | 700 | 700 | |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 3 | 1 | 1 | 1 | Shifts |
| Theoretical Output | 718867,4274 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 195,8333333 | 195,8333333 | 195,8333333 | 195,8333333 | R/hr |
| Nr Workers | 6 | 6 | 6 | 6 | Workers |
| Yearly Wage | 7021800 | 2340600 | 2340600 | 2340600 | |
| Waste Treatment Cost | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 2400 | 800 | 800 | 800 | kWh/day |

**Figure A.25:** Process Inputs for EB CHM Process

| Capital Investment | Lang Factor | Cost |
|---|---|---|
| Equipment | 1 | R 303 255 019,22 |
| Adjusting to Smallest International Capacity | 100,4016064 | R 94 578 750,16 |
| Erection of items | 0,11 | R 10 403 662,52 |
| Structural and Buildings | 0,26 | R 24 590 475,04 |
| Civils | 0,17 | R 16 078 387,53 |
| Piping & Ducting | 0,14 | R 13 241 025,02 |
| Electrical | 0,26 | R 24 590 475,04 |
| Instruments | 0,1 | R 9 457 875,02 |
| | | R 192 940 650,33 |
| Installed Plant | | |
| GST | 0,13 | R 25 082 284,54 |
| Site Prep | 0,05 | R 10 901 146,74 |
| Construction Management | 0,15 | R 34 338 612,24 |
| Contingency | 0,15 | R 39 489 404,08 |
| | | R 109 811 447,61 |
| FCI | | R 302 752 097,94 |
| Initial Loan | | 302752097,94 |
| Annual Interest Rate | | 10,5% |
| Years | | 10 |
| Total Compounding Periods | | 120 |
| Compounding Periods Per Year | | 12 |
| Effective Annual Interest Rate | | 11,02035% |
| Future Value | | 861217584,8 |
| Monthly Installment | | R 4 085 185,34 |
| Yearly Total | | R 49 022 224,03 |
| Discounting Factor | | 7% |
| Depreciation | | |
| Fixed Capital Investment | R 302 752 097,94 | |
| Salvage Value | 0 | |
| Life of Equipment | 10 | |

**Figure A.26:** Capital Investment Cost Input and Calculations for EB CHM Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 11 501 878,84 |
| Waste Treatment | | | | R 1 171 753,91 |
| Utilities | | | | R 597 600,00 |
| Operating Labour | | | | R 7 021 800,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 1 228 815,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 18 165 125,88 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 2 724 768,88 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 1 053 270,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 3 607 911,53 |
| DMC | | | | R 47 072 924,03 |
| | | | | |
| Depreciation | | | 0,1 | R 30 275 209,79 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 9 688 067,13 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 11 636 364,53 |
| FMC | | | | R 51 599 641,45 |
| | | | | |
| Administration | | | 0,15 | R 3 962 361,13 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 13 229 008,95 |
| Research and Development | | | 0,05 | R 6 013 185,89 |
| GE | | | | R 23 204 555,96 |
| | | | | |
| COM | | | | R 120 263 717,70 |
| COM_d | | | | R 89 988 507,91 |
| | | | | |
| Income | | | | R 187 105 216,53 |

**Figure A.27:** Cost of Manufacturing Calculations for EB CHM Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 887 492,32 |
| Waste Treatment | | | | R 90 413,28 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 18 165 125,88 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 2 724 768,88 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 2 778 247,96 |
| DMC | | | | R 27 946 543,32 |
| | | | | |
| Depreciation | | | 0,1 | R 30 275 209,79 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 9 688 067,13 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 11 144 838,53 |
| FMC | | | | R 51 108 115,45 |
| | | | | |
| Administration | | | 0,15 | R 3 137 299,63 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 10 186 909,18 |
| Research and Development | | | 0,05 | R 4 630 413,27 |
| GE | | | | R 17 954 622,08 |
| | | | | |
| COM | | | | R 92 608 265,31 |
| COM_d | | | | R 62 333 055,52 |
| | | | | |
| Income | | | | R 14 437 158,05 |

**Figure A.28:** Cost of Manufacturing Calculations for EB CHM Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 1 806 924,56 |
| Waste Treatment | | | | R 184 080,44 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 18 165 125,88 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 2 724 768,88 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 2 815 631,33 |
| DMC | | | | R 28 997 026,08 |
| | | | | |
| Depreciation | | | 0,1 | R 30 275 209,79 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 9 688 067,13 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 11 144 838,53 |
| FMC | | | | R 51 108 115,45 |
| | | | | |
| Administration | | | 0,15 | R 3 137 299,63 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 10 323 981,53 |
| Research and Development | | | 0,05 | R 4 692 718,88 |
| GE | | | | R 18 154 000,04 |
| | | | | |
| | | | | |
| COM | | | | R 93 854 377,57 |
| COM_d | | | | R 63 579 167,78 |
| | | | | |
| Income | | | | R 29 393 894,32 |

**Figure A.29:** Cost of Manufacturing Calculations for EB CHM Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 2 726 356,80 |
| Waste Treatment | | | | R 277 747,60 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 18 165 125,88 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 2 724 768,88 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 2 853 014,70 |
| DMC | | | | R 30 047 508,85 |
| | | | | |
| Depreciation | | | 0,1 | R 30 275 209,79 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 9 688 067,13 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 11 144 838,53 |
| FMC | | | | R 51 108 115,45 |
| | | | | |
| Administration | | | 0,15 | R 3 137 299,63 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 10 461 053,88 |
| Research and Development | | | 0,05 | R 4 755 024,49 |
| GE | | | | R 18 353 378,00 |
| | | | | |
| | | | | |
| COM | | | | R 95 100 489,83 |
| COM_d | | | | R 64 825 280,04 |
| | | | | |
| Income | | | | R 44 350 630,58 |

**Figure A.30:** Cost of Manufacturing Calculations for EB CHM Process Best-Case

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Throughput | 164,801139 | 27,84551707 | 56,69316516 | 85,54081325 | kg/hr |
| Actual Max Cap | 450 | 450 | 450 | 450 | |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 3 | 1 | 1 | 1 | Shifts |
| Theoretical Output | 984851,6067 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 7358,79 | 195,8333333 | 195,8333333 | 195,8333333 | R/hr |
| Nr Workers | 6 | 6 | 6 | 6 | Workers |
| Yearly Wage | 263856774,2 | 2340600 | 2340600 | 2340600 | |
| Waste Treatment Cost | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 2400 | 800 | 800 | 800 | kWh/day |

**Figure A.31:** Process Inputs for PA CHM Process

| Capital Investment | Lang Factor | | | Cost |
|---|---|---|---|---|
| Equipment | 1 | | | R 330 012 815,04 |
| Adjusting to Smallest International Capacity | 100,4016064 | | | R 134 167 613,05 |
| Erection of items | 0,11 | | | R 14 758 437,44 |
| Structural and Buildings | 0,26 | | | R 34 883 579,39 |
| Civils | 0,17 | | | R 22 808 494,22 |
| Piping & Ducting | 0,14 | | | R 18 783 465,83 |
| Electrical | 0,26 | | | R 34 883 579,39 |
| Instruments | 0,1 | | | R 13 416 761,30 |
| | | | | R 273 701 930,61 |
| | | | | |
| Installed Plant | | | | |
| GST | 0,13 | | | R 35 581 250,98 |
| Site Prep | 0,05 | | | R 15 464 159,08 |
| Construction Management | 0,15 | | | R 48 712 101,10 |
| Contingency | 0,15 | | | R 56 018 916,27 |
| | | | | R 155 776 427,43 |
| | | | | |
| FCI | | | | R 429 478 358,04 |
| | | | | |
| Initial Loan | | | | 429478358,04 |
| Annual Interest Rate | | | | 10,5% |
| Years | | | | 10 |
| Total Compounding Periods | | | | 120 |
| Compounding Periods Per Year | | | | 12 |
| Effective Annual Interest Rate | | | | 11,02035% |
| Future Value | | | | 1221706858 |
| Monthly Installment | | | | R 5 795 166,09 |
| Yearly Total | | | | R 69 541 993,03 |
| | | | | |
| Discounting Factor | | | | 7% |
| | | | | |
| Depreciation | | | | |
| Fixed Capital Investment | 429478358 | | | |
| Salvage Value | 0 | | | |
| Life of Equipment | 10 | | | |

**Figure A.32:** Capital Investment Cost Input and Calculations for PA CHM Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 15 757 625,71 |
| Waste Treatment | | | | R 1 605 308,12 |
| Utilities | | | | R 597 600,00 |
| Operating Labour | | | | R 7 021 800,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 1 228 815,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 25 768 701,48 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 3 865 305,22 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 1 053 270,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 4 845 447,33 |
| DMC | | | | R 61 743 872,86 |
| | | | | |
| Depreciation | | | 0,1 | R 42 947 835,80 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 13 743 307,46 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 16 198 509,89 |
| FMC | | | | R 72 889 653,15 |
| | | | | |
| Administration | | | 0,15 | R 5 102 897,47 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 17 766 640,19 |
| Research and Development | | | 0,05 | R 8 075 745,54 |
| GE | | | | R 30 945 283,21 |
| | | | | |
| COM | | | | R 161 514 910,86 |
| COM_d | | | | R 118 567 075,05 |
| | | | | |
| Income | | | | R 256 334 987,62 |

**Figure A.33:** Cost of Manufacturing Calculations for PA CHM Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 887 492,32 |
| Waste Treatment | | | | R 90 413,28 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 25 768 701,48 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 3 865 305,22 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 3 842 748,54 |
| DMC | | | | R 37 755 155,85 |
| | | | | |
| Depreciation | | | 0,1 | R 42 947 835,80 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 13 743 307,46 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 15 706 983,89 |
| FMC | | | | R 72 398 127,15 |
| | | | | |
| Administration | | | 0,15 | R 4 277 835,97 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 14 090 078,00 |
| Research and Development | | | 0,05 | R 6 404 580,91 |
| GE | | | | R 24 772 494,87 |
| | | | | |
| COM | | | | R 128 091 618,14 |
| COM_d | | | | R 85 143 782,34 |
| | | | | |
| Income | | | | R 14 437 158,05 |

**Figure A.34:** Cost of Manufacturing Calculations for PA CHM Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 1 806 924,56 |
| Waste Treatment | | | | R 184 080,44 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 25 768 701,48 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 3 865 305,22 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 3 880 131,91 |
| DMC | | | | R 38 805 638,62 |
| | | | | |
| Depreciation | | | 0,1 | R 42 947 835,80 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 13 743 307,46 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 15 706 983,89 |
| FMC | | | | R 72 398 127,15 |
| | | | | |
| Administration | | | 0,15 | R 4 277 835,97 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 14 227 150,34 |
| Research and Development | | | 0,05 | R 6 466 886,52 |
| GE | | | | R 24 971 872,84 |
| | | | | |
| COM | | | | R 129 337 730,40 |
| COM_d | | | | R 86 389 894,60 |
| | | | | |
| Income | | | | R 29 393 894,32 |

Figure A.35: Cost of Manufacturing Calculations for PA CHM Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 2 726 356,80 |
| Waste Treatment | | | | R 277 747,60 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 2 340 600,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 409 605,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 25 768 701,48 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 3 865 305,22 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 351 090,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 3 917 515,28 |
| DMC | | | | R 39 856 121,38 |
| | | | | |
| Depreciation | | | 0,1 | R 42 947 835,80 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 13 743 307,46 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 15 706 983,89 |
| FMC | | | | R 72 398 127,15 |
| | | | | |
| Administration | | | 0,15 | R 4 277 835,97 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 14 364 222,69 |
| Research and Development | | | 0,05 | R 6 529 192,13 |
| GE | | | | R 25 171 250,80 |
| | | | | |
| COM | | | | R 130 583 842,66 |
| COM_d | | | | R 87 636 006,86 |
| | | | | |
| Income | | | | R 44 350 630,58 |

Figure A.36: Cost of Manufacturing Calculations for PA CHM Process Best-Case

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Throughput | 84,05660396 | 27,84551707 | 56,69316516 | 85,54081325 | kg/hr |
| Actual Max Cap | 700 | 700 | 700 | 700 | |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 3 | 1 | 1 | 1 | Shifts |
| Theoretical Output | 502322,2653 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 195,8333333 | 195,8333333 | 195,8333333 | 195,8333333 | R/hr |
| Nr Workers | 10 | 10 | 10 | 10 | Workers |
| Yearly Wage | 11703000 | 3901000 | 3901000 | 3901000 | |
| Waste Treatment Cost | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 2400 | 800 | 800 | 800 | kWh/day |

**Figure A.37:** Process Inputs for Mill Product Production Process

| Capital Investment | Lang Factor | Cost |
|---|---|---|
| Equipment | 1 | R 682 026 484,41 |
| Adjusting to Smallest International Capacity | 100,4016064 | R 212 709 463,60 |
| Erection of items | 0,11 | R 23 398 041,00 |
| Structural and Buildings | 0,26 | R 55 304 460,54 |
| Civils | 0,17 | R 36 160 608,81 |
| Piping & Ducting | 0,14 | R 29 779 324,90 |
| Electrical | 0,26 | R 55 304 460,54 |
| Instruments | 0,1 | R 21 270 946,36 |
| | | R 433 927 305,75 |
| | | |
| Installed Plant | | |
| GST | 0,13 | R 56 410 549,75 |
| Site Prep | 0,05 | R 24 516 892,77 |
| Construction Management | 0,15 | R 77 228 212,24 |
| Contingency | 0,15 | R 88 812 444,08 |
| | | R 246 968 098,84 |
| | | |
| FCI | | R 680 895 404,59 |
| | | |
| Initial Loan | | 680895404,59 |
| Annual Interest Rate | | 10,5% |
| Years | | 10 |
| Total Compounding Periods | | 120 |
| Compounding Periods Per Year | | 12 |
| Effective Annual Interest Rate | | 11,02035% |
| Future Value | | 1936895235 |
| Monthly Installment | | R 9 187 661,92 |
| Yearly Total | | R 110 251 943,07 |
| | | |
| Discounting Factor | | 7% |
| | | |
| Depreciation | | |
| Fixed Capital Investment | 680895404,6 | |
| Salvage Value | 0 | |
| Life of Equipment | 10 | |

**Figure A.38:** Capital Investment Cost Input and Calculations for Mill Product Production Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 8 037 156,24 |
| Waste Treatment | | | | R 818 785,29 |
| Utilities | | | | R 597 600,00 |
| Operating Labour | | | | R 11 703 000,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 2 048 025,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 40 853 724,28 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 6 128 058,64 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 1 755 450,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 7 026 832,78 |
| DMC | | | | R 78 968 632,23 |
| | | | | |
| Depreciation | | | 0,1 | R 68 089 540,46 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 21 788 652,95 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 25 741 049,57 |
| FMC | | | | R 115 619 242,97 |
| | | | | |
| Administration | | | 0,15 | R 8 190 712,39 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 25 765 053,53 |
| Research and Development | | | 0,05 | R 11 711 387,97 |
| GE | | | | R 45 667 153,89 |
| | | | | |
| COM | | | | R 234 227 759,37 |
| COM_d | | | | R 166 138 218,92 |
| | | | | |
| Income | | | | R 384 555 600,87 |

**Figure A.39:** Cost of Manufacturing Calculations for Mill Product Production Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 887 492,32 |
| Waste Treatment | | | | R 90 413,28 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 3 901 000,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 682 675,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 40 853 724,28 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 6 128 058,64 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 585 150,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 6 082 448,50 |
| DMC | | | | R 59 410 162,01 |
| | | | | |
| Depreciation | | | 0,1 | R 68 089 540,46 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 21 788 652,95 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 24 921 839,57 |
| FMC | | | | R 114 800 032,97 |
| | | | | |
| Administration | | | 0,15 | R 6 815 609,89 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 22 302 311,15 |
| Research and Development | | | 0,05 | R 10 137 414,16 |
| GE | | | | R 39 255 335,20 |
| | | | | |
| COM | | | | R 202 748 283,17 |
| COM_d | | | | R 134 658 742,71 |
| | | | | |
| Income | | | | R 42 464 042,26 |

**Figure A.40:** Cost of Manufacturing Calculations for Mill Product Production Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 1 806 924,56 |
| Waste Treatment | | | | R 184 080,44 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 3 901 000,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 682 675,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 40 853 724,28 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 6 128 058,64 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 585 150,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 6 119 831,86 |
| DMC | | | | R 60 460 644,78 |
| | | | | |
| Depreciation | | | 0,1 | R 68 089 540,46 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 21 788 652,95 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 24 921 839,57 |
| FMC | | | | R 114 800 032,97 |
| | | | | |
| Administration | | | 0,15 | R 6 815 609,89 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 22 439 383,50 |
| Research and Development | | | 0,05 | R 10 199 719,77 |
| GE | | | | R 39 454 713,16 |
| | | | | |
| | | | | |
| COM | | | | R 203 994 395,43 |
| COM_d | | | | R 135 904 854,98 |
| | | | | |
| Income | | | | R 86 456 320,96 |

**Figure A.41:** Cost of Manufacturing Calculations for Mill Product Production Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 2 726 356,80 |
| Waste Treatment | | | | R 277 747,60 |
| Utilities | | | | R 199 200,00 |
| Operating Labour | | | | R 3 901 000,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 682 675,00 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 40 853 724,28 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 6 128 058,64 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 585 150,00 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 6 157 215,23 |
| DMC | | | | R 61 511 127,55 |
| | | | | |
| Depreciation | | | 0,1 | R 68 089 540,46 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 21 788 652,95 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 24 921 839,57 |
| FMC | | | | R 114 800 032,97 |
| | | | | |
| Administration | | | 0,15 | R 6 815 609,89 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 22 576 455,85 |
| Research and Development | | | 0,05 | R 10 262 025,38 |
| GE | | | | R 39 654 091,12 |
| | | | | |
| | | | | |
| COM | | | | R 205 240 507,70 |
| COM_d | | | | R 137 150 967,24 |
| | | | | |
| Income | | | | R 130 448 599,67 |

**Figure A.42:** Cost of Manufacturing Calculations for Mill Product Production Process Best-Case

| | BE | Worst | Base | Best | |
|---|---|---|---|---|---|
| Throughput | 6,509515442 | 9,281839023 | 18,89772172 | 28,51360442 | kg/hr |
| Workdays | 249 | 249 | 249 | 249 | Days |
| Shift Length | 8 | 8 | 8 | 8 | hrs |
| Shifts/Day | 3 | 3 | 3 | 3 | Shifts |
| Theoretical Output | 38900,86428 | 55468,27 | 112932,785 | 170397,3 | kg/yr |
| Wage | 115,4166667 | 115,4166667 | 115,4166667 | 115,4166667 | R/hr |
| Nr Workers | 3 | 3 | 3 | 3 | Workers |
| Yearly Wage | 2069190 | 2069190 | 2069190 | 2069190 | |
| Waste Treatment Cost | 1,63 | 1,63 | 1,63 | 1,63 | R/kg |
| Electricity Use | 660,8 | 660,8 | 660,8 | 660,8 | kWh/day |

**Figure A.43:** Process Inputs for Precision Casting Process

| | | | | |
|---|---|---|---|---|
| Capital Investment | Lang Factor | | | Cost |
| Equipment | 1 | | | R 20 137 500,00 |
| Erection of items | 0,11 | | | R 2 215 125,00 |
| Structural and Buildings | 0,26 | | | R 5 235 750,00 |
| Civils | 0,17 | | | R 3 423 375,00 |
| Piping & Ducting | 0,14 | | | R 2 819 250,00 |
| Electrical | 0,26 | | | R 5 235 750,00 |
| Instruments | 0,1 | | | R 2 013 750,00 |
| | | | | R 41 080 500,00 |
| | | | | |
| Installed Plant | | | | |
| GST | 0,13 | | | R 5 340 465,00 |
| Site Prep | 0,05 | | | R 2 321 048,25 |
| Construction Management | 0,15 | | | R 7 311 301,99 |
| Contingency | 0,15 | | | R 8 407 997,29 |
| | | | | R 23 380 812,52 |
| | | | | |
| FCI | | | | R 64 461 312,52 |
| | | | | |
| Initial Loan | | | | 64461312,52 |
| Annual Interest Rate | | | | 10,5% |
| Years | | | | 10 |
| Total Compounding Periods | | | | 120 |
| Compounding Periods Per Year | | | | 12 |
| Effective Annual Interest Rate | | | | 11,02035% |
| Future Value | | | | 183368558,8 |
| Monthly Installment | | | | R 869 808,70 |
| Yearly Total | | | | R 10 437 704,40 |
| | | | | |
| Discounting Factor | | | | 7% |
| | | | | |
| Depreciation | | | | |
| Fixed Capital Investment | R 64 461 312,52 | | 15000 | |
| Salvage Value | 0 | | | |
| Life of Equipment | 10 | | | |

**Figure A.44:** Capital Investment Cost Input and Calculations for Precision Casting Process

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 622 413,83 |
| Waste Treatment | | | | R 63 408,41 |
| Utilities | | | | R 103 659,70 |
| Operating Labour | | | | R 2 069 190,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 362 108,25 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 3 867 678,75 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 580 151,81 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 310 378,50 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 740 073,57 |
| DMC | | | | R 8 719 062,82 |
| | | | | |
| Depreciation | | | 0,1 | R 6 446 131,25 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 2 062 762,00 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 2 537 872,20 |
| FMC | | | | R 11 046 765,45 |
| | | | | |
| Administration | | | 0,15 | R 944 846,55 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 2 713 603,09 |
| Research and Development | | | 0,05 | R 1 233 455,95 |
| GE | | | | R 4 891 905,59 |
| | | | | |
| COM | | | | R 24 669 118,98 |
| COM_d | | | | R 18 222 987,73 |
| | | | | |
| Income | | | | R 38 900 864,28 |

**Figure A.45:** Cost of Manufacturing Calculations for Precision Casting Process Break-Even

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 887 492,32 |
| Waste Treatment | | | | R 90 413,28 |
| Utilities | | | | R 103 659,70 |
| Operating Labour | | | | R 2 069 190,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 362 108,25 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 3 867 678,75 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 580 151,81 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 310 378,50 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 750 851,45 |
| DMC | | | | R 9 021 924,06 |
| | | | | |
| Depreciation | | | 0,1 | R 6 446 131,25 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 2 062 762,00 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 2 537 872,20 |
| FMC | | | | R 11 046 765,45 |
| | | | | |
| Administration | | | 0,15 | R 944 846,55 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 2 753 121,97 |
| Research and Development | | | 0,05 | R 1 251 419,08 |
| GE | | | | R 4 949 387,59 |
| | | | | |
| COM | | | | R 25 028 381,52 |
| COM_d | | | | R 18 582 250,27 |
| | | | | |
| Income | | | | R 55 468 270,00 |

**Figure A.46:** Cost of Manufacturing Calculations for Precision Casting Process Worst-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 1 806 924,56 |
| Waste Treatment | | | | R 184 080,44 |
| Utilities | | | | R 103 659,70 |
| Operating Labour | | | | R 2 069 190,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 362 108,25 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 3 867 678,75 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 580 151,81 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 310 378,50 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 788 234,81 |
| DMC | | | | R 10 072 406,82 |
| | | | | |
| Depreciation | | | 0,1 | R 6 446 131,25 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 2 062 762,00 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 2 537 872,20 |
| FMC | | | | R 11 046 765,45 |
| | | | | |
| Administration | | | 0,15 | R 944 846,55 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 2 890 194,32 |
| Research and Development | | | 0,05 | R 1 313 724,69 |
| GE | | | | R 5 148 765,56 |
| | | | | |
| COM | | | | R 26 274 493,78 |
| COM_d | | | | R 19 828 362,53 |
| | | | | |
| Income | | | | R 112 932 785,00 |

**Figure A.47:** Cost of Manufacturing Calculations for Precision Casting Process Average-Case

| Manufacturing Costs | Min Range | Max Range | Midpoint | |
|---|---|---|---|---|
| Raw Materials | | | | R 2 726 356,80 |
| Waste Treatment | | | | R 277 747,60 |
| Utilities | | | | R 103 659,70 |
| Operating Labour | | | | R 2 069 190,00 |
| Direct Supervisory and Clerical Labour | 0,1 | 0,25 | 0,175 | R 362 108,25 |
| Maintenance and Repairs | 0,02 | 0,1 | 0,06 | R 3 867 678,75 |
| Operating Supplies | 0,1 | 0,2 | 0,15 | R 580 151,81 |
| Laboritory Charges | 0,1 | 0,2 | 0,15 | R 310 378,50 |
| Patents and Royalties | 0 | 0,06 | 0,03 | R 825 618,18 |
| DMC | | | | R 11 122 889,59 |
| | | | | |
| Depreciation | | | 0,1 | R 6 446 131,25 |
| Local Taxes and Insurance | 0,014 | 0,05 | 0,032 | R 2 062 762,00 |
| Plant Overhead Costs | 0,5 | 0,7 | 0,6 | R 2 537 872,20 |
| FMC | | | | R 11 046 765,45 |
| | | | | |
| Administration | | | 0,15 | R 944 846,55 |
| Distribution and Selling | 0,02 | 0,2 | 0,11 | R 3 027 266,66 |
| Research and Development | | | 0,05 | R 1 376 030,30 |
| GE | | | | R 5 348 143,52 |
| | | | | |
| COM | | | | R 27 520 606,04 |
| COM_d | | | | R 21 074 474,79 |
| | | | | |
| Income | | | | R 170 397 300,00 |

**Figure A.48:** Cost of Manufacturing Calculations for Precision Casting Process Best-Case

# Appendix B

# Feasibility Study NPV Analyses Full Results

| | Year | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Revenue from Annual Sales | | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 | R 6 545 151,68 |
| Total Annual Expense | | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 | R 5 045 039,56 |
| Annual Cash Flow | | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 | R 1 500 112,12 |
| Annual Depreciation and Other Tax Allowances | | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 |
| Amount of Tax | | R 155 623,97 | R 155 623,97 | R 155 623,97 | R 155 623,97 | R 155 623,97 | R 155 623,97 | R 155 623,97 | R 155 623,97 | R 155 623,97 | R 155 623,97 |
| Total Annual Capital Expendi | R 9 443 122,13 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 443 122,13 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 | R 1 344 488,15 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash | -R 9 443 122,13 | R 1 256 530,98 | R 1 174 328,02 | R 1 097 502,82 | R 1 025 703,57 | R 958 601,47 | R 895 889,22 | R 837 279,65 | R 782 504,34 | R 731 312,47 | R 683 469,60 |
| Net Present Value | -R 9 443 122,13 | -R 8 186 591,15 | -R 7 012 263,14 | -R 5 914 760,32 | -R 4 889 056,75 | -R 3 930 455,28 | -R 3 034 566,06 | -R 2 197 286,41 | -R 1 414 782,07 | -R 683 469,60 | R 0,00 |

**Figure B.1:** NPV Analysis for Wash and Briquette Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 | R 5 254 077,80 |
| Total Annual Expense | | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 | R 4 749 472,08 |
| Annual Cash Flow | | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 |
| Annual Depreciation and Other Tax Allowances | | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expendi | R 9 443 122,13 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 443 122,13 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 | R 504 605,71 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash | -R 9 443 122,13 | R 471 594,13 | R 440 742,17 | R 411 908,57 | R 384 961,28 | R 359 776,90 | R 336 240,09 | R 314 243,08 | R 293 685,12 | R 274 472,07 | R 256 515,96 |
| Net Present Value | -R 9 443 122,13 | -R 8 971 528,01 | -R 8 530 785,83 | -R 8 118 877,26 | -R 7 733 915,98 | -R 7 374 139,08 | -R 7 037 898,99 | -R 6 723 655,91 | -R 6 429 970,79 | -R 6 155 498,71 | -R 5 898 982,76 |

**Figure B.2:** NPV Analysis for Wash and Briquette Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 | R 10 697 244,36 |
| Total Annual Expense | | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 | R 6 313 421,37 |
| Annual Cash Flow | | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 | R 4 383 822,99 |
| Annual Depreciation and Other Tax Allowances | | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 |
| Amount of Tax | | R 963 063,02 | R 963 063,02 | R 963 063,02 | R 963 063,02 | R 963 063,02 | R 963 063,02 | R 963 063,02 | R 963 063,02 | R 963 063,02 | R 963 063,02 |
| Total Annual Capital Expendi | R 9 443 122,13 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 443 122,13 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 | R 3 420 759,97 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash | -R 9 443 122,13 | R 3 196 971,93 | R 2 987 824,24 | R 2 792 359,10 | R 2 609 681,40 | R 2 438 954,58 | R 2 279 396,81 | R 2 130 277,39 | R 1 990 913,45 | R 1 860 666,77 | R 1 738 940,91 |
| Net Present Value | -R 9 443 122,13 | -R 6 246 150,20 | -R 3 258 325,96 | -R 465 966,86 | R 2 143 714,54 | R 4 582 669,12 | R 6 862 065,93 | R 8 992 343,32 | R 10 983 256,76 | R 12 843 923,54 | R 14 582 864,45 |

**Figure B.3:** NPV Analysis for Wash and Briquette Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 | R 16 140 410,92 |
| Total Annual Expense | | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 | R 7 559 533,63 |
| Annual Cash Flow | | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 | R 8 580 877,28 |
| Annual Depreciation and Other Tax Allowances | | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 | R 944 312,21 |
| Amount of Tax | | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 | R 2 138 238,22 |
| Total Annual Capital Expendi | R 9 443 122,13 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 443 122,13 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 | R 6 442 639,06 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash | -R 9 443 122,13 | R 6 021 158,00 | R 5 627 250,47 | R 5 259 112,59 | R 4 915 058,50 | R 4 593 512,61 | R 4 293 002,44 | R 4 012 151,81 | R 3 749 674,59 | R 3 504 368,78 | R 3 275 111,01 |
| Net Present Value | -R 9 443 122,13 | -R 3 421 964,13 | R 2 205 286,34 | R 7 464 398,93 | R 12 379 457,43 | R 16 972 970,04 | R 21 265 972,48 | R 25 278 124,30 | R 29 027 798,89 | R 32 532 167,67 | R 35 807 278,68 |

**Figure B.4:** NPV Analysis for Wash and Briquette Process Best-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 | R 5 744 210,97 |
| Total Annual Expense | | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 | R 4 279 592,74 |
| Annual Cash Flow | | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 | R 1 464 618,23 |
| Annual Depreciation and Other Tax Allowances | | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 |
| Amount of Tax | | R 151 941,78 | R 151 941,78 | R 151 941,78 | R 151 941,78 | R 151 941,78 | R 151 941,78 | R 151 941,78 | R 151 941,78 | R 151 941,78 | R 151 941,78 |
| Total Annual Capital Expenditure | R 9 219 690,05 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 219 690,05 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 | R 1 312 676,45 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 9 219 690,05 | R 1 226 800,42 | R 1 146 542,45 | R 1 071 535,00 | R 1 001 434,58 | R 935 920,16 | R 874 691,74 | R 817 468,92 | R 763 989,64 | R 714 009,01 | R 667 298,14 |
| Net Present Value | -R 9 219 690,05 | -R 7 992 889,64 | -R 6 846 347,19 | -R 5 774 812,20 | -R 4 773 377,62 | -R 3 837 457,46 | -R 2 962 765,71 | -R 2 145 296,80 | -R 1 381 307,15 | -R 667 298,14 | R 0,00 |

**Figure B.5:** NPV Analysis for Thermal Degreasing Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 | R 1 679 455,95 |
| Total Annual Expense | | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 | R 3 886 031,41 |
| Annual Cash Flow | | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 |
| Annual Depreciation and Other Tax Allowances | | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 9 219 690,05 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 219 690,05 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 | -R 2 206 575,46 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 9 219 690,05 | -R 2 062 220,05 | -R 1 927 308,46 | -R 1 801 222,86 | -R 1 683 385,85 | -R 1 573 257,80 | -R 1 470 334,40 | -R 1 374 144,30 | -R 1 284 247,01 | -R 1 200 230,85 | -R 1 121 711,07 |
| Net Present Value | -R 9 219 690,05 | -R 11 281 910,11 | -R 13 209 218,56 | -R 15 010 441,42 | -R 16 693 827,27 | -R 18 267 085,08 | -R 19 737 419,48 | -R 21 111 563,77 | -R 22 395 810,78 | -R 23 596 041,62 | -R 24 717 752,69 |

**Figure B.6:** NPV Analysis for Thermal Degreasing Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 | R 3 419 353,77 |
| Total Annual Expense | | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 | R 4 054 493,35 |
| Annual Cash Flow | | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 |
| Annual Depreciation and Other Tax Allowances | | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 9 219 690,05 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 219 690,05 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 | -R 635 139,58 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 9 219 690,05 | -R 593 588,39 | -R 554 755,51 | -R 518 463,09 | -R 484 544,94 | -R 452 845,74 | -R 423 220,32 | -R 395 533,01 | -R 369 657,02 | -R 345 473,85 | -R 322 872,76 |
| Net Present Value | -R 9 219 690,05 | -R 9 813 278,44 | -R 10 368 033,95 | -R 10 886 497,04 | -R 11 371 041,98 | -R 11 823 887,72 | -R 12 247 108,04 | -R 12 642 641,05 | -R 13 012 298,07 | -R 13 357 771,92 | -R 13 680 644,67 |

**Figure B.7:** NPV Analysis for Thermal Degreasing Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 | R 5 159 251,58 |
| Total Annual Expense | | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 | R 4 222 955,28 |
| Annual Cash Flow | | R 936 296,30 | R 936 296,30 | R 936 296,30 | R 936 296,30 | R 936 296,30 | R 936 296,30 | R 936 296,30 | R 936 296,30 | R 936 296,30 | R 936 296,30 |
| Annual Depreciation and Other Tax Allowances | | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 | R 921 969,01 |
| Amount of Tax | | R 4 011,64 | R 4 011,64 | R 4 011,64 | R 4 011,64 | R 4 011,64 | R 4 011,64 | R 4 011,64 | R 4 011,64 | R 4 011,64 | R 4 011,64 |
| Total Annual Capital Expenditure | R 9 219 690,05 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 9 219 690,05 | R 932 284,66 | R 932 284,66 | R 932 284,66 | R 932 284,66 | R 932 284,66 | R 932 284,66 | R 932 284,66 | R 932 284,66 | R 932 284,66 | R 932 284,66 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 9 219 690,05 | R 871 294,07 | R 814 293,53 | R 761 021,99 | R 711 235,50 | R 664 706,08 | R 621 220,63 | R 580 580,03 | R 542 598,16 | R 507 101,08 | R 473 926,25 |
| Net Present Value | -R 9 219 690,05 | -R 8 348 395,98 | -R 7 534 102,46 | -R 6 773 080,47 | -R 6 061 844,97 | -R 5 397 138,89 | -R 4 775 918,26 | -R 4 195 338,23 | -R 3 652 740,07 | -R 3 145 638,99 | -R 2 671 712,75 |

**Figure B.8:** NPV Analysis for Thermal Degreasing Process Best-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 | R 15 870 516,13 |
| Total Annual Expense | | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 | R 12 622 392,00 |
| Annual Cash Flow | | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 | R 3 248 124,13 |
| Annual Depreciation and Other Tax Allowances | | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 |
| Amount of Tax | | R 336 965,47 | R 336 965,47 | R 336 965,47 | R 336 965,47 | R 336 965,47 | R 336 965,47 | R 336 965,47 | R 336 965,47 | R 336 965,47 | R 336 965,47 |
| Total Annual Capital Expenditure | R 20 446 760,21 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 20 446 760,21 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 | R 2 911 158,66 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 20 446 760,21 | R 2 720 709,03 | R 2 542 718,72 | R 2 376 372,63 | R 2 220 909,00 | R 2 075 615,89 | R 1 939 827,93 | R 1 812 923,30 | R 1 694 320,84 | R 1 583 477,42 | R 1 479 885,44 |
| Net Present Value | -R 20 446 760,21 | -R 17 726 051,18 | -R 15 183 332,47 | -R 12 806 959,84 | -R 10 586 050,84 | -R 8 510 434,95 | -R 6 570 607,01 | -R 4 757 683,71 | -R 3 063 362,87 | -R 1 479 885,44 | R 0,00 |

**Figure B.9:** NPV Analysis for Ferrotitanium Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 | R 4 543 313,55 |
| Total Annual Expense | | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 | R 9 109 351,87 |
| Annual Cash Flow | | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 |
| Annual Depreciation and Other Tax Allowances | | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 20 446 760,21 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 20 446 760,21 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 | -R 4 566 038,32 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 20 446 760,21 | -R 4 267 325,53 | -R 3 988 154,70 | -R 3 727 247,38 | -R 3 483 408,77 | -R 3 255 522,22 | -R 3 042 544,13 | -R 2 843 499,18 | -R 2 657 475,87 | -R 2 483 622,31 | -R 2 321 142,35 |
| Net Present Value | -R 20 446 760,21 | -R 24 714 085,74 | -R 28 702 240,44 | -R 32 429 487,83 | -R 35 912 896,60 | -R 39 168 418,81 | -R 42 210 962,94 | -R 45 054 462,12 | -R 47 711 938,00 | -R 50 195 560,31 | -R 52 516 702,65 |

**Figure B.10:** NPV Analysis for Ferrotitanium Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 | R 9 250 136,20 |
| Total Annual Expense | | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 | R 11 261 126,98 |
| Annual Cash Flow | | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 |
| Annual Depreciation and Other Tax Allowances | | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 20 446 760,21 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 20 446 760,21 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 | -R 2 010 990,78 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 20 446 760,21 | -R 1 879 430,63 | -R 1 756 477,23 | -R 1 641 567,50 | -R 1 534 175,24 | -R 1 433 808,63 | -R 1 340 008,07 | -R 1 252 343,99 | -R 1 170 414,94 | -R 1 093 845,74 | -R 1 022 285,74 |
| Net Present Value | -R 20 446 760,21 | -R 22 326 190,84 | -R 24 082 668,07 | -R 25 724 235,57 | -R 27 258 410,81 | -R 28 692 219,44 | -R 30 032 227,51 | -R 31 284 571,50 | -R 32 454 986,44 | -R 33 548 832,18 | -R 34 571 117,92 |

**Figure B.11:** NPV Analysis for Ferrotitanium Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 | R 13 956 958,85 |
| Total Annual Expense | | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 | R 12 228 931,41 |
| Annual Cash Flow | | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 |
| Annual Depreciation and Other Tax Allowances | | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 | R 2 044 676,02 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 20 446 760,21 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 20 446 760,21 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 | R 1 728 027,44 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 20 446 760,21 | R 1 614 978,92 | R 1 509 326,09 | R 1 410 585,13 | R 1 318 303,86 | R 1 232 059,68 | R 1 151 457,65 | R 1 076 128,64 | R 1 005 727,70 | R 939 932,43 | R 878 441,53 |
| Net Present Value | -R 20 446 760,21 | -R 18 831 781,30 | -R 17 322 455,21 | -R 15 911 870,08 | -R 14 593 566,22 | -R 13 361 506,53 | -R 12 210 048,89 | -R 11 133 920,25 | -R 10 128 192,54 | -R 9 188 260,11 | -R 8 309 818,59 |

**Figure B.12:** NPV Analysis for Ferrotitanium Process Best-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 | R 445 822 803,62 |
| Total Annual Expense | | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 | R 372 833 572,30 |
| Annual Cash Flow | | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 | R 72 989 231,32 |
| Annual Depreciation and Other Tax Allowances | | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 |
| Amount of Tax | | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 | R 7 572 016,85 |
| Total Annual Capital Expenditure | R 459 463 140,02 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 459 463 140,02 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 | R 65 417 214,47 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 459 463 140,02 | R 61 137 583,62 | R 57 137 928,61 | R 53 399 933,28 | R 49 906 479,71 | R 46 641 569,82 | R 43 590 252,17 | R 40 738 553,43 | R 38 073 414,42 | R 35 582 630,30 | R 33 254 794,67 |
| Net Present Value | -R 459 463 140,02 | -R 398 325 556,40 | -R 341 187 627,79 | -R 287 787 694,50 | -R 237 881 214,79 | -R 191 239 644,98 | -R 147 649 392,81 | -R 106 910 839,38 | -R 68 837 424,97 | -R 33 254 794,67 | R 0,00 |

**Figure B.13:** NPV Analysis for VAR Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 |
| Total Annual Expense | | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 | R 170 076 955,24 |
| Annual Cash Flow | | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 |
| Annual Depreciation and Other Tax Allowances | | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 459 463 140,02 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 459 463 140,02 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 | -R 155 639 797,18 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 459 463 140,02 | -R 145 457 754,38 | -R 135 941 826,52 | -R 127 048 436,00 | -R 118 736 856,07 | -R 110 969 024,37 | -R 103 709 368,57 | -R 96 924 643,52 | -R 90 583 778,99 | -R 84 657 737,38 | -R 79 119 380,73 |
| Net Present Value | -R 459 463 140,02 | -R 604 920 894,39 | -R 740 862 720,91 | -R 867 911 156,91 | -R 986 648 012,99 | -R 1 097 617 037,36 | -R 1 201 326 405,92 | -R 1 298 251 049,45 | -R 1 388 834 828,44 | -R 1 473 492 565,82 | -R 1 552 611 946,54 |

**Figure B.14:** NPV Analysis for VAR Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 |
| Total Annual Expense | | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 | R 176 646 728,14 |
| Annual Cash Flow | | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 |
| Annual Depreciation and Other Tax Allowances | | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 459 463 140,02 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 459 463 140,02 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 | -R 147 252 833,82 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 459 463 140,02 | -R 137 619 470,86 | -R 128 616 327,91 | -R 120 202 175,61 | -R 112 338 481,88 | -R 104 989 235,40 | -R 98 120 780,75 | -R 91 701 664,25 | -R 85 702 489,96 | -R 80 095 785,01 | -R 74 855 873,84 |
| Net Present Value | -R 459 463 140,02 | -R 597 082 610,88 | -R 725 698 938,78 | -R 845 901 114,39 | -R 958 239 596,28 | -R 1 063 228 831,68 | -R 1 161 349 612,43 | -R 1 253 051 276,68 | -R 1 338 753 766,64 | -R 1 418 849 551,64 | -R 1 493 705 425,48 |

**Figure B.15:** NPV Analysis for VAR Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 |
| Total Annual Expense | | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 | R 183 216 501,04 |
| Annual Cash Flow | | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 |
| Annual Depreciation and Other Tax Allowances | | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 | R 45 946 314,00 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 459 463 140,02 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 459 463 140,02 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 | -R 138 865 870,46 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 459 463 140,02 | -R 129 781 187,34 | -R 121 290 829,29 | -R 113 355 915,23 | -R 105 940 107,69 | -R 99 009 446,44 | -R 92 532 192,93 | -R 86 478 684,98 | -R 80 821 200,92 | -R 75 533 832,63 | -R 70 592 366,95 |
| Net Present Value | -R 459 463 140,02 | -R 589 244 327,36 | -R 710 535 156,65 | -R 823 891 071,88 | -R 929 831 179,56 | -R 1 028 840 626,00 | -R 1 121 372 818,93 | -R 1 207 851 503,92 | -R 1 288 672 704,83 | -R 1 364 206 537,47 | -R 1 434 798 904,42 |

**Figure B.16:** NPV Analysis for VAR Process Best-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 | R 187 105 216,53 |
| Total Annual Expense | | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 | R 139 010 731,94 |
| Annual Cash Flow | | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 | R 48 094 484,59 |
| Annual Depreciation and Other Tax Allowances | | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 |
| Amount of Tax | | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 | R 4 989 396,94 |
| Total Annual Capital Expenditure | R 302 752 097,94 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 302 752 097,94 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 | R 43 105 087,65 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 302 752 097,94 | R 40 285 128,65 | R 37 649 652,94 | R 35 186 591,53 | R 32 884 664,98 | R 30 733 331,76 | R 28 722 739,96 | R 26 843 682,21 | R 25 087 553,47 | R 23 446 311,65 | R 21 912 440,79 |
| Net Present Value | -R 302 752 097,94 | -R 262 466 969,30 | -R 224 817 316,36 | -R 189 630 724,82 | -R 156 746 059,84 | -R 126 012 728,08 | -R 97 289 988,12 | -R 70 446 305,91 | -R 45 358 752,44 | -R 21 912 440,79 | R 0,00 |

**Figure B.17:** NPV Analysis for EB CHM Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 |
| Total Annual Expense | | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 | R 111 355 279,55 |
| Annual Cash Flow | | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 |
| Annual Depreciation and Other Tax Allowances | | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 302 752 097,94 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 302 752 097,94 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 | -R 96 918 121,50 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 302 752 097,94 | -R 90 577 683,64 | -R 84 652 040,79 | -R 79 114 056,81 | -R 73 938 370,85 | -R 69 101 281,17 | -R 64 580 636,61 | -R 60 355 735,15 | -R 56 407 229,11 | -R 52 717 036,55 | -R 49 268 258,46 |
| Net Present Value | -R 302 752 097,94 | -R 393 329 781,58 | -R 477 981 822,37 | -R 557 095 879,18 | -R 631 034 250,03 | -R 700 135 531,20 | -R 764 716 167,80 | -R 825 071 902,95 | -R 881 479 132,06 | -R 934 196 168,61 | -R 983 464 427,07 |

**Figure B.18:** NPV Analysis for EB CHM Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 |
| Total Annual Expense | | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 | R 112 601 391,81 |
| Annual Cash Flow | | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 |
| Annual Depreciation and Other Tax Allowances | | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 302 752 097,94 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 302 752 097,94 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 | -R 83 207 497,49 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 302 752 097,94 | -R 77 764 016,35 | -R 72 676 650,79 | -R 67 922 103,54 | -R 63 478 601,44 | -R 59 325 795,74 | -R 55 444 668,92 | -R 51 817 447,59 | -R 48 427 521,11 | -R 45 259 365,52 | -R 42 298 472,45 |
| Net Present Value | -R 302 752 097,94 | -R 380 516 114,29 | -R 453 192 765,08 | -R 521 114 868,63 | -R 584 593 470,07 | -R 643 919 265,81 | -R 699 363 934,73 | -R 751 181 382,32 | -R 799 608 903,42 | -R 844 868 268,95 | -R 887 166 741,40 |

**Figure B.19:** NPV Analysis for EB CHM Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 |
| Total Annual Expense | | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 | R 113 847 504,07 |
| Annual Cash Flow | | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 |
| Annual Depreciation and Other Tax Allowances | | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 | R 30 275 209,79 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 302 752 097,94 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 302 752 097,94 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 | -R 69 496 873,49 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 302 752 097,94 | -R 64 950 349,05 | -R 60 701 260,80 | -R 56 730 150,28 | -R 53 018 832,04 | -R 49 550 310,31 | -R 46 308 701,23 | -R 43 279 160,03 | -R 40 447 813,11 | -R 37 801 694,49 | -R 35 328 686,44 |
| Net Present Value | -R 302 752 097,94 | -R 367 702 447,00 | -R 428 403 707,80 | -R 485 133 858,07 | -R 538 152 690,11 | -R 587 703 000,43 | -R 634 011 701,65 | -R 677 290 861,68 | -R 717 738 674,79 | -R 755 540 369,28 | -R 790 869 055,73 |

**Figure B.20:** NPV Analysis for EB CHM Process Best-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 | R 256 334 987,62 |
| Total Annual Expense | | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 | R 188 109 068,08 |
| Annual Cash Flow | | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 | R 68 225 919,54 |
| Annual Depreciation and Other Tax Allowances | | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 |
| Amount of Tax | | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 | R 7 077 863,45 |
| Total Annual Capital Expenditure | R 429 478 358,04 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 429 478 358,04 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 | R 61 148 056,09 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 429 478 358,04 | R 57 147 715,97 | R 53 409 080,35 | R 49 915 028,36 | R 46 649 559,22 | R 43 597 718,90 | R 40 745 531,68 | R 38 079 936,15 | R 35 588 725,37 | R 33 260 491,00 | R 31 084 571,03 |
| Net Present Value | -R 429 478 358,04 | -R 372 330 642,06 | -R 318 921 561,71 | -R 269 006 533,35 | -R 222 356 974,13 | -R 178 759 255,23 | -R 138 013 723,55 | -R 99 933 787,41 | -R 64 345 062,03 | -R 31 084 571,03 | R 0,00 |

**Figure B.21:** NPV Analysis for PA CHM Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 | R 14 437 158,05 |
| Total Annual Expense | | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 | R 154 685 775,36 |
| Annual Cash Flow | | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 |
| Annual Depreciation and Other Tax Allowances | | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 429 478 358,04 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 429 478 358,04 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 | -R 140 248 617,31 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 429 478 358,04 | -R 131 073 474,12 | -R 122 498 573,95 | -R 114 484 648,55 | -R 106 994 998,64 | -R 99 995 325,83 | -R 93 453 575,55 | -R 87 339 790,23 | -R 81 625 972,18 | -R 76 285 955,31 | -R 71 295 285,33 |
| Net Present Value | -R 429 478 358,04 | -R 560 551 832,16 | -R 683 050 406,11 | -R 797 535 054,66 | -R 904 530 053,30 | -R 1 004 525 379,13 | -R 1 097 978 954,68 | -R 1 185 318 744,91 | -R 1 266 944 717,09 | -R 1 343 230 672,39 | -R 1 414 525 957,73 |

**Figure B.22:** NPV Analysis for PA CHM Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 | R 29 393 894,32 |
| Total Annual Expense | | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 | R 155 931 887,63 |
| Annual Cash Flow | | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 |
| Annual Depreciation and Other Tax Allowances | | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 429 478 358,04 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 429 478 358,04 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 | -R 126 537 993,31 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 429 478 358,04 | -R 118 259 806,83 | -R 110 523 183,95 | -R 103 292 695,28 | -R 96 535 229,24 | -R 90 219 840,41 | -R 84 317 607,86 | -R 78 801 502,67 | -R 73 646 264,18 | -R 68 828 284,28 | -R 64 325 499,33 |
| Net Present Value | -R 429 478 358,04 | -R 547 738 164,87 | -R 658 261 348,82 | -R 761 554 044,10 | -R 858 089 273,34 | -R 948 309 113,75 | -R 1 032 626 721,61 | -R 1 111 428 224,28 | -R 1 185 074 488,45 | -R 1 253 902 772,73 | -R 1 318 228 272,06 |

**Figure B.23:** NPV Analysis for PA CHM Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 | R 44 350 630,58 |
| Total Annual Expense | | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 | R 157 177 999,89 |
| Annual Cash Flow | | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 |
| Annual Depreciation and Other Tax Allowances | | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 | R 42 947 835,80 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 429 478 358,04 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 429 478 358,04 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 | -R 112 827 369,30 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 429 478 358,04 | -R 105 446 139,54 | -R 98 547 793,96 | -R 92 100 742,02 | -R 86 075 459,83 | -R 80 444 354,98 | -R 75 181 640,17 | -R 70 263 215,11 | -R 65 666 556,18 | -R 61 370 613,25 | -R 57 355 713,32 |
| Net Present Value | -R 429 478 358,04 | -R 534 924 497,58 | -R 633 472 291,53 | -R 725 573 033,55 | -R 811 648 493,38 | -R 892 092 848,36 | -R 967 274 488,53 | -R 1 037 537 703,64 | -R 1 103 204 259,82 | -R 1 164 574 873,07 | -R 1 221 930 586,39 |

**Figure B.24:** NPV Analysis for PA CHM Process Best-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 | R 384 555 600,87 |
| Total Annual Expense | | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 | R 276 390 161,98 |
| Annual Cash Flow | | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 | R 108 165 438,88 |
| Annual Depreciation and Other Tax Allowances | | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 |
| Amount of Tax | | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 | R 11 221 251,56 |
| Total Annual Capital Expenditure | R 680 895 404,59 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 680 895 404,59 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 | R 96 944 187,32 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 680 895 404,59 | R 90 602 044,23 | R 84 674 807,69 | R 79 135 334,29 | R 73 958 256,35 | R 69 119 865,74 | R 64 598 005,37 | R 60 371 967,63 | R 56 422 399,66 | R 52 731 214,63 | R 49 281 509,00 |
| Net Present Value | -R 680 895 404,59 | -R 590 293 360,36 | -R 505 618 552,67 | -R 426 483 218,38 | -R 352 524 962,04 | -R 283 405 096,29 | -R 218 807 090,93 | -R 158 435 123,29 | -R 102 012 723,64 | -R 49 281 509,00 | R 0,00 |

**Figure B.25:** NPV Analysis for Mill Product Production Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 | R 42 464 042,26 |
| Total Annual Expense | | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 | R 244 910 685,78 |
| Annual Cash Flow | | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 |
| Annual Depreciation and Other Tax Allowances | | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 680 895 404,59 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 680 895 404,59 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 | -R 202 446 643,53 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 680 895 404,59 | -R 189 202 470,58 | -R 176 824 738,86 | -R 165 256 765,29 | -R 154 445 575,04 | -R 144 341 658,92 | -R 134 898 746,65 | -R 126 073 595,00 | -R 117 825 789,72 | -R 110 117 560,49 | -R 102 913 607,93 |
| Net Present Value | -R 680 895 404,59 | -R 870 097 875,17 | -R 1 046 922 614,03 | -R 1 212 179 379,33 | -R 1 366 624 954,37 | -R 1 510 966 613,28 | -R 1 645 865 359,94 | -R 1 771 938 954,94 | -R 1 889 764 744,66 | -R 1 999 882 305,14 | -R 2 102 795 913,07 |

**Figure B.26:** NPV Analysis for Mill Product Production Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 | R 86 456 320,96 |
| Total Annual Expense | | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 | R 246 156 798,04 |
| Annual Cash Flow | | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 |
| Annual Depreciation and Other Tax Allowances | | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 680 895 404,59 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 680 895 404,59 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 | -R 159 700 477,08 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 680 895 404,59 | -R 149 252 782,32 | -R 139 488 581,61 | -R 130 363 160,38 | -R 121 834 729,33 | -R 113 864 233,02 | -R 106 415 171,04 | -R 99 453 430,88 | -R 92 947 131,66 | -R 86 866 478,19 | -R 81 183 624,48 |
| Net Present Value | -R 680 895 404,59 | -R 830 148 186,91 | -R 969 636 768,51 | -R 1 099 999 928,89 | -R 1 221 834 658,22 | -R 1 335 698 891,23 | -R 1 442 114 062,28 | -R 1 541 567 493,16 | -R 1 634 514 624,82 | -R 1 721 381 103,01 | -R 1 802 564 727,49 |

**Figure B.27:** NPV Analysis for Mill Product Production Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 | R 130 448 599,67 |
| Total Annual Expense | | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 | R 247 402 910,30 |
| Annual Cash Flow | | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 |
| Annual Depreciation and Other Tax Allowances | | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 | R 68 089 540,46 |
| Amount of Tax | | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Total Annual Capital Expenditure | R 680 895 404,59 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 680 895 404,59 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 | -R 116 954 310,64 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 680 895 404,59 | -R 109 303 094,05 | -R 102 152 424,35 | -R 95 469 555,47 | -R 89 223 883,61 | -R 83 386 807,11 | -R 77 931 595,43 | -R 72 833 266,76 | -R 68 068 473,61 | -R 63 615 395,90 | -R 59 453 641,02 |
| Net Present Value | -R 680 895 404,59 | -R 790 198 498,64 | -R 892 350 922,99 | -R 987 820 478,45 | -R 1 077 044 362,07 | -R 1 160 431 169,18 | -R 1 238 362 764,62 | -R 1 311 196 031,38 | -R 1 379 264 504,99 | -R 1 442 879 900,88 | -R 1 502 333 541,91 |

**Figure B.28:** NPV Analysis for Mill Product Production Process Best-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 | R 38 900 864,28 |
| Total Annual Expense | | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 | R 28 660 692,13 |
| Annual Cash Flow | | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 | R 10 240 172,15 |
| Annual Depreciation and Other Tax Allowances | | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 |
| Amount of Tax | | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 | R 1 062 331,45 |
| Total Annual Capital Expenditure | R 64 461 312,52 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 64 461 312,52 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 | R 9 177 840,70 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 64 461 312,52 | R 8 577 421,21 | R 8 016 281,51 | R 7 491 851,88 | R 7 001 730,73 | R 6 543 673,58 | R 6 115 582,78 | R 5 715 497,93 | R 5 341 586,85 | R 4 992 137,24 | R 4 665 548,82 |
| Net Present Value | -R 64 461 312,52 | -R 55 883 891,31 | -R 47 867 609,80 | -R 40 375 757,92 | -R 33 374 027,20 | -R 26 830 353,62 | -R 20 714 770,84 | -R 14 999 272,91 | -R 9 657 686,06 | -R 4 665 548,82 | R 0,00 |

**Figure B.29:** NPV Analysis for Precision Casting Process Break-Even

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 | R 55 468 270,00 |
| Total Annual Expense | | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 | R 29 019 954,67 |
| Annual Cash Flow | | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 | R 26 448 315,33 |
| Annual Depreciation and Other Tax Allowances | | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 |
| Amount of Tax | | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 | R 5 600 611,54 |
| Total Annual Capital Expenditure | R 64 461 312,52 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 64 461 312,52 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 | R 20 847 703,79 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 64 461 312,52 | R 19 483 835,32 | R 18 209 191,89 | R 17 017 936,34 | R 15 904 613,40 | R 14 864 124,68 | R 13 891 705,31 | R 12 982 902,16 | R 12 133 553,42 | R 11 339 769,55 | R 10 597 915,47 |
| Net Present Value | -R 64 461 312,52 | -R 44 977 477,20 | -R 26 768 285,32 | -R 9 750 348,97 | R 6 154 264,43 | R 21 018 389,11 | R 34 910 094,41 | R 47 892 996,57 | R 60 026 549,99 | R 71 366 319,53 | R 81 964 235,00 |

**Figure B.30:** NPV Analysis for Precision Casting Process Worst-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 | R 112 932 785,00 |
| Total Annual Expense | | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 | R 30 266 066,93 |
| Annual Cash Flow | | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 | R 82 666 718,07 |
| Annual Depreciation and Other Tax Allowances | | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 |
| Amount of Tax | | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 | R 21 341 764,31 |
| Total Annual Capital Expenditure | R 64 461 312,52 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 64 461 312,52 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 | R 61 324 953,76 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 64 461 312,52 | R 57 313 040,90 | R 53 563 589,63 | R 50 059 429,56 | R 46 784 513,61 | R 43 723 844,49 | R 40 863 406,07 | R 38 190 099,13 | R 35 691 681,43 | R 33 356 711,61 | R 31 174 496,84 |
| Net Present Value | -R 64 461 312,52 | -R 7 148 271,62 | R 46 415 318,00 | R 96 474 747,56 | R 143 259 261,17 | R 186 983 105,66 | R 227 846 511,72 | R 266 036 610,85 | R 301 728 292,28 | R 335 085 003,89 | R 366 259 500,73 |

**Figure B.31:** NPV Analysis for Precision Casting Process Average-Case

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue from Annual Sales | | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 | R 170 397 300,00 |
| Total Annual Expense | | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 | R 31 512 179,19 |
| Annual Cash Flow | | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 | R 138 885 120,81 |
| Annual Depreciation and Other Tax Allowances | | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 | R 6 446 131,25 |
| Amount of Tax | | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 | R 37 082 917,08 |
| Total Annual Capital Expenditure | R 64 461 312,52 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 | R 0,00 |
| Net Annual Cash Flow | -R 64 461 312,52 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 | R 101 802 203,74 |
| Discount Factor | 1,00 | 0,93 | 0,87 | 0,82 | 0,76 | 0,71 | 0,67 | 0,62 | 0,58 | 0,54 | 0,51 |
| Net Annual Discounted Cash Flow | -R 64 461 312,52 | R 95 142 246,48 | R 88 917 987,37 | R 83 100 922,77 | R 77 664 413,81 | R 72 583 564,30 | R 67 835 106,83 | R 63 397 296,10 | R 59 249 809,44 | R 55 373 653,68 | R 51 751 078,21 |
| Net Present Value | -R 64 461 312,52 | R 30 680 933,96 | R 119 598 921,32 | R 202 699 844,10 | R 280 364 257,90 | R 352 947 822,21 | R 420 782 929,03 | R 484 180 225,13 | R 543 430 034,57 | R 598 803 688,25 | R 650 554 766,46 |

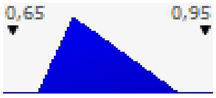
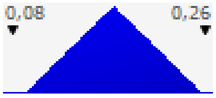
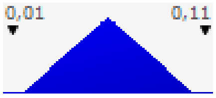
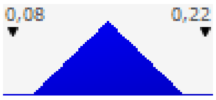
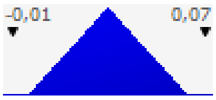
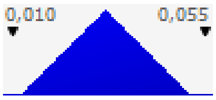
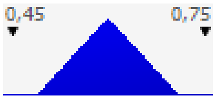
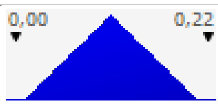
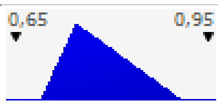
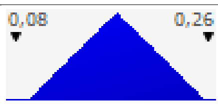
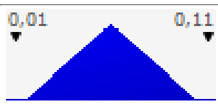
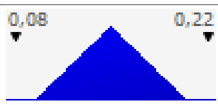
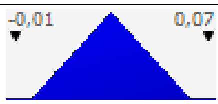
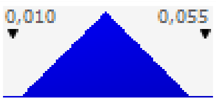
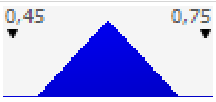
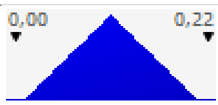
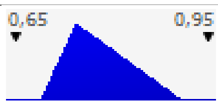
**Figure B.32:** NPV Analysis for Precision Casting Process Best-Case

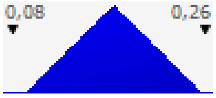
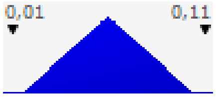
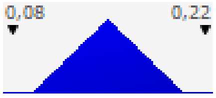
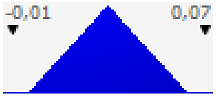
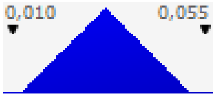
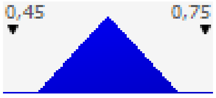
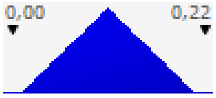
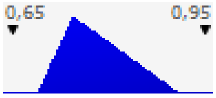
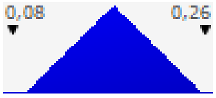
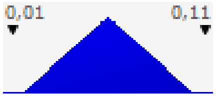
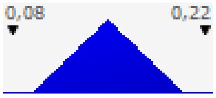
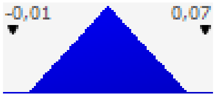
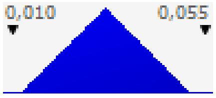
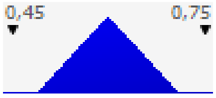
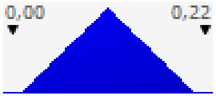
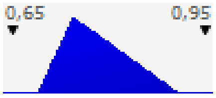
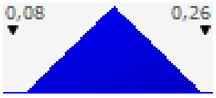
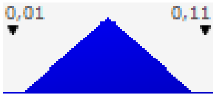
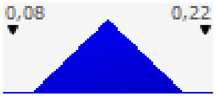
# Appendix C

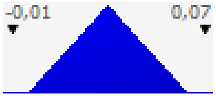
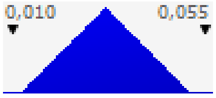
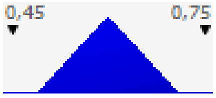
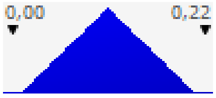
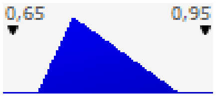
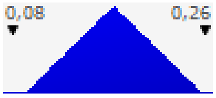
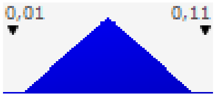
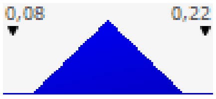
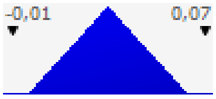
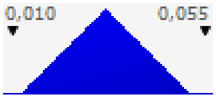
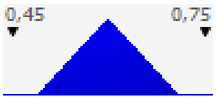
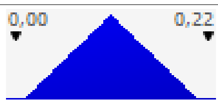
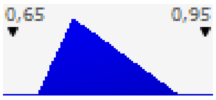
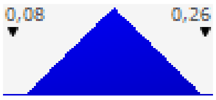
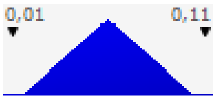
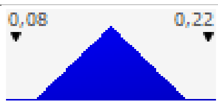
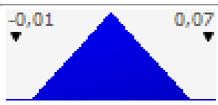
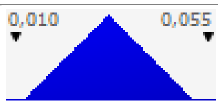
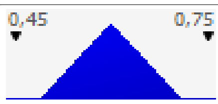
# Simulation Inputs

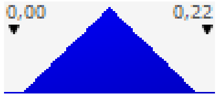
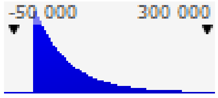
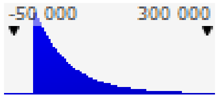
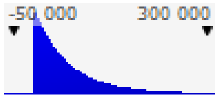
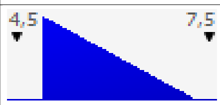
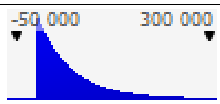
# @RISK Model Inputs

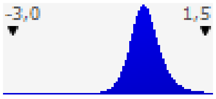
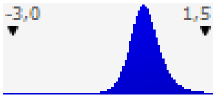
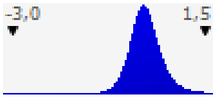
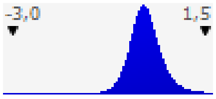
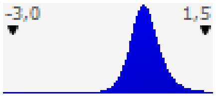
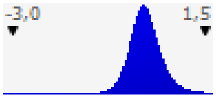
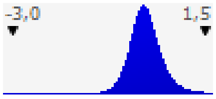
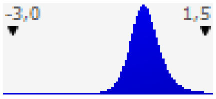
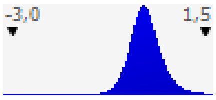
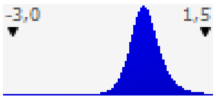
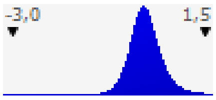
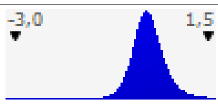
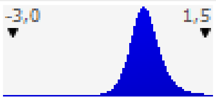
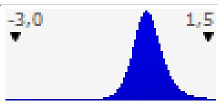
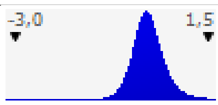
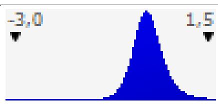
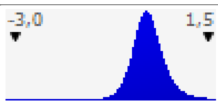
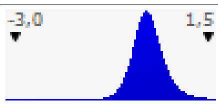
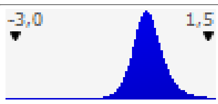
**Performed By:** Wilhelm
**Date:** 31 August 2016 11:52:23 PM

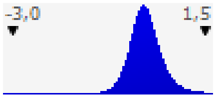
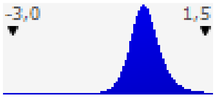
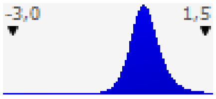
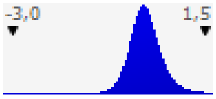
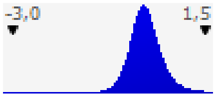
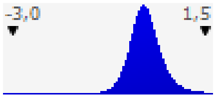
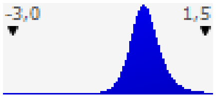
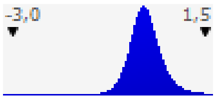
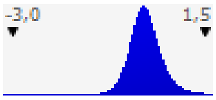
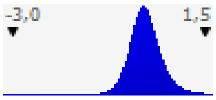
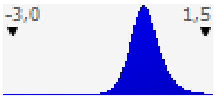
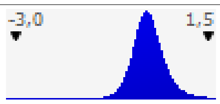
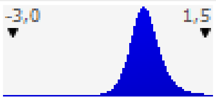
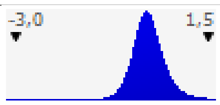
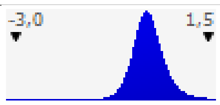
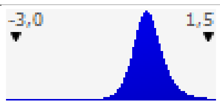
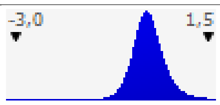
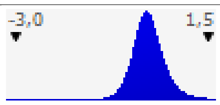
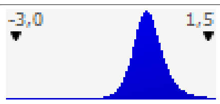
| | Name | Cell | Graph | Function | Min | Mean | Max |
|---|---|---|---|---|---|---|---|
| | Efficiency | I29 |   | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Factor | I42 |   | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor | I45 |   | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor | I51 |   | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor | I54 |   | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor | I61 |   | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor | I64 |   | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor | I71 |   | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Efficiency | N29 |   | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Factor | N42 |   | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor | N45 |   | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor | N51 |   | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor | N54 |   | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor | N61 |   | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor | N64 |   | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor | N71 |   | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Efficiency | O29 |   | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |

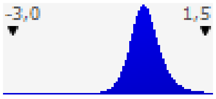
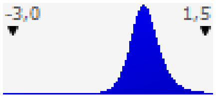
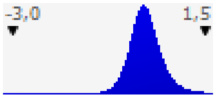
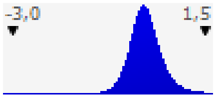
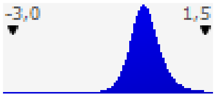
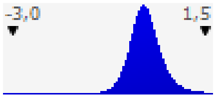
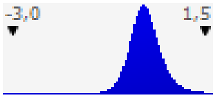
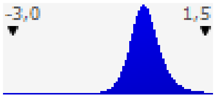
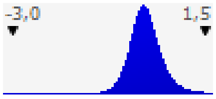
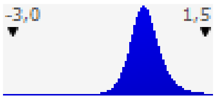
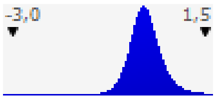
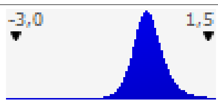
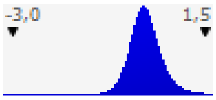
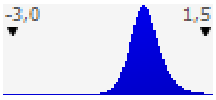
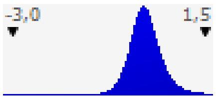
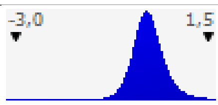
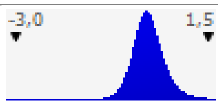
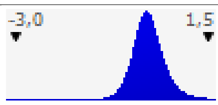
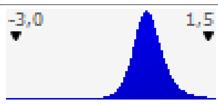
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Factor | O42 |  | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor | O45 |  | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor | O51 |  | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor | O54 |  | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor | O61 |  | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor | O64 |  | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor | O71 |  | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Efficiency | P29 |  | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Factor | P42 |  | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor | P45 |  | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor | P51 |  | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor | P54 |  | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor | P61 |  | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor | P64 |  | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor | P71 |  | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Efficiency | Q29 |  | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Factor | Q42 |  | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor | Q45 |  | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor | Q51 |  | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |

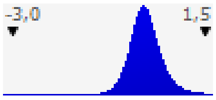
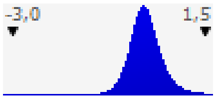
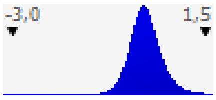
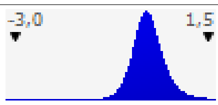
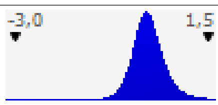
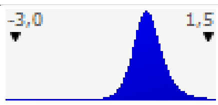
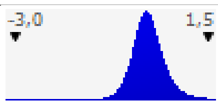
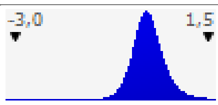
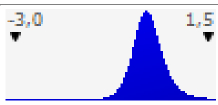
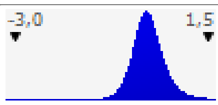
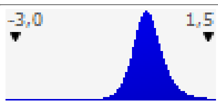
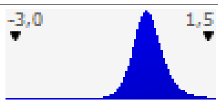
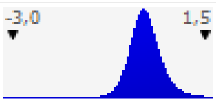
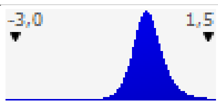
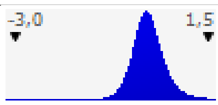
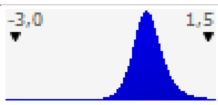
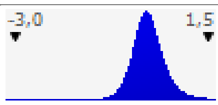
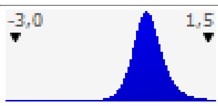
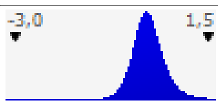
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Factor | Q54 |  | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor | Q61 |  | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor | Q64 |  | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor | Q71 |  | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Efficiency | R29 |  | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Factor | R42 |  | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor | R45 |  | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor | R51 |  | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor | R54 |  | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor | R61 |  | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor | R64 |  | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor | R71 |  | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Efficiency | S29 |  | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Factor | S42 |  | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor | S45 |  | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor | S51 |  | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor | S54 |  | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor | S61 |  | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor | S64 |  | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |

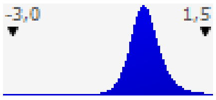
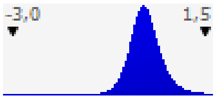
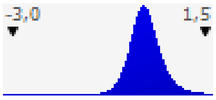
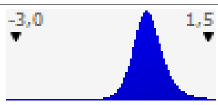
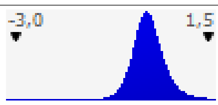
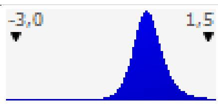
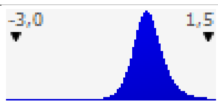
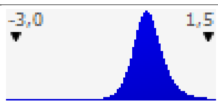
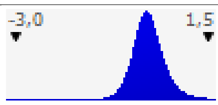
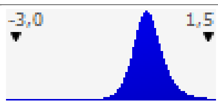
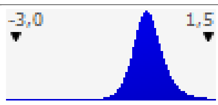
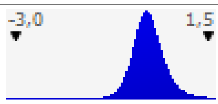
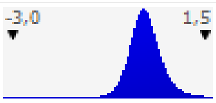
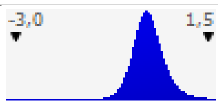
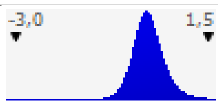
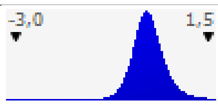
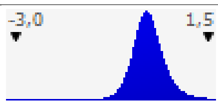
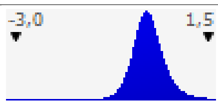
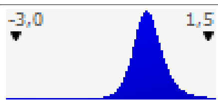
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Factor | S71 |  | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Low Scrap Price | AK297 |  | RiskUniform(1,46667;2,13333;RiskName ("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AK298 |  | RiskUniform(1,67222;2,22778;RiskName ("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Low Scrap Price | AK301 |  | RiskUniform(1,46667;2,13333;RiskName ("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AK302 |  | RiskUniform(1,67222;2,22778;RiskName ("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Scrap | AL7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| | Elect Growth | AL289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| | Low Scrap Price | AL301 |  | RiskUniform(1,46667;2,13333;RiskName ("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AL302 |  | RiskUniform(1,67222;2,22778;RiskName ("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Scrap | AM7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| | Elect Growth | AM289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| | Low Scrap Price | AM301 |  | RiskUniform(1,46667;2,13333;RiskName ("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AM302 |  | RiskUniform(1,67222;2,22778;RiskName ("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Scrap | AN7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| | Elect Growth | AN289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| | Low Scrap Price | AN301 |  | RiskUniform(1,46667;2,13333;RiskName ("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AN302 |  | RiskUniform(1,67222;2,22778;RiskName ("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | RepoRate | AN309 |  | RiskTriang(5;5;7,1861;RiskName("Repo Rate")) | 5 | 5,7287 | 7,1861 |
| | Scrap | AO7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |

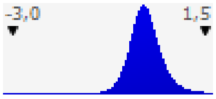
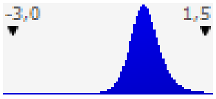
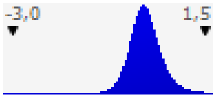
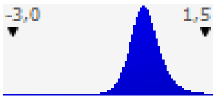
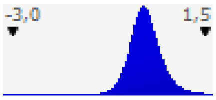
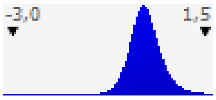
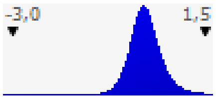
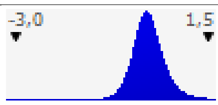
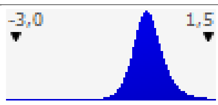
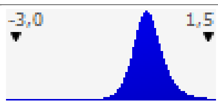
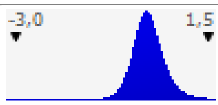
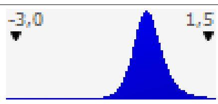
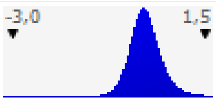
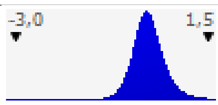
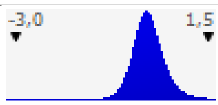
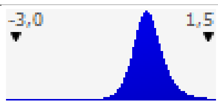
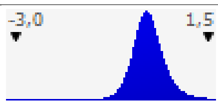
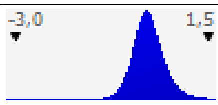
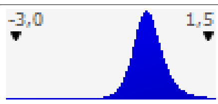
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Growth | AO15 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO16 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO17 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO18 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO19 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO20 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO21 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO22 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO23 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO24 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO25 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO26 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO27 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO28 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO29 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO30 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO31 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO32 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO33 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |

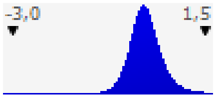
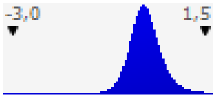
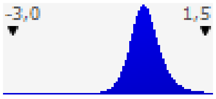
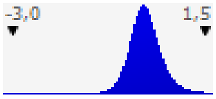
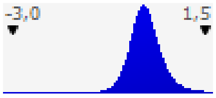
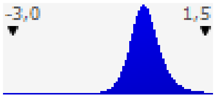
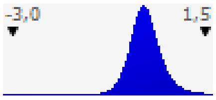
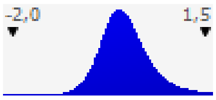
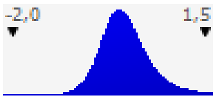
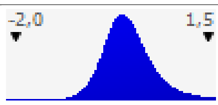
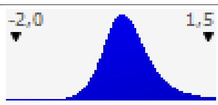
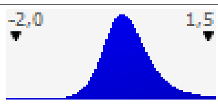
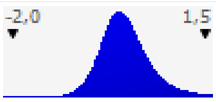
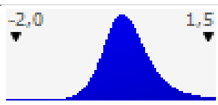
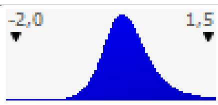
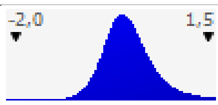
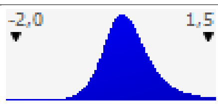
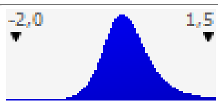
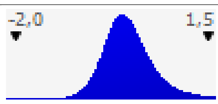
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Growth | AO34 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO35 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO36 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO37 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO38 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO39 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO40 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO41 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO42 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO43 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO44 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO45 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO46 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO47 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO48 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO49 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO50 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO51 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO52 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |

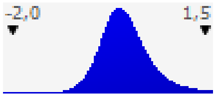
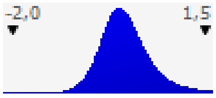
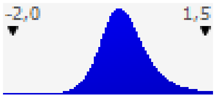
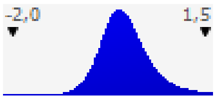
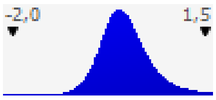
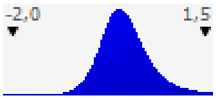
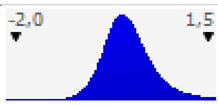
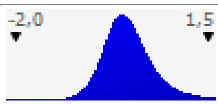
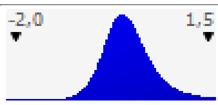
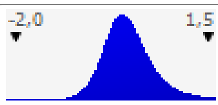
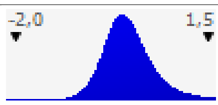
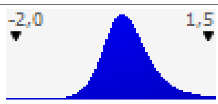
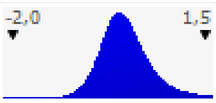
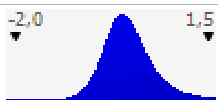
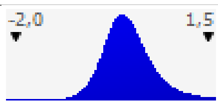
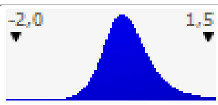
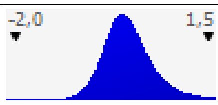
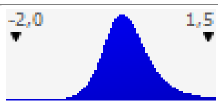
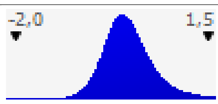
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Growth | AO53 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO54 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO55 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO56 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO57 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO58 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO59 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO60 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO61 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO62 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO63 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO64 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO65 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO66 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO67 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO68 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO69 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO70 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO71 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |

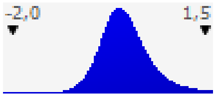
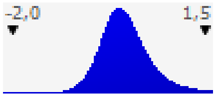
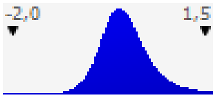
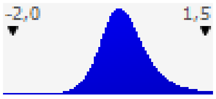
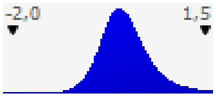
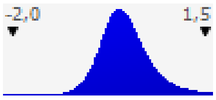
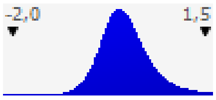
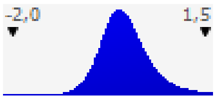
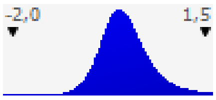
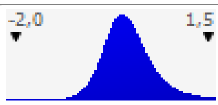
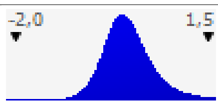
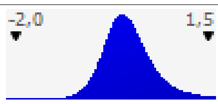
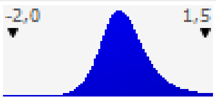
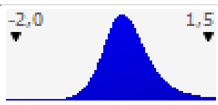
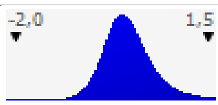
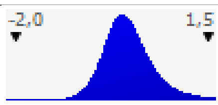
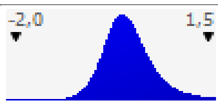
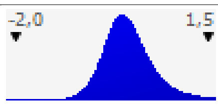
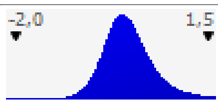
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Growth | AO72 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO73 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO74 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO75 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO76 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO77 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO78 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO79 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO80 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO81 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO82 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO83 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO84 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO85 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO86 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO87 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO88 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO89 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO90 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Growth | AO91 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO92 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO93 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO94 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO95 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO96 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO97 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO98 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO99 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO100 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO101 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO102 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO103 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO104 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO105 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO106 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO107 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO108 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO109 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Growth | AO110 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO111 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO112 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO113 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO114 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO115 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO116 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO117 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO118 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO119 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO120 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO121 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO122 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO123 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO124 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO125 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO126 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO127 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO128 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Growth | AO129 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO130 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO131 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO132 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO133 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO134 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Growth | AO135 |  | RiskLoglogistic(-2,5223;2,5696;13,882;RiskName("Growth")) | -2,5223 | 0,069365 | +∞ |
| | Euro Growth | AO150 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO151 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO152 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO153 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO154 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO155 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO156 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO157 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO158 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO159 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO160 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO161 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Euro Growth | AO162 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO163 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO164 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO165 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO166 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO167 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO168 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO169 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO170 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO171 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO172 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO173 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO174 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO175 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO176 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO177 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO178 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO179 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO180 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Euro Growth | AO181 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO182 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO183 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO184 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO185 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO186 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO187 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO188 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO189 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO190 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO191 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO192 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO193 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO194 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO195 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO196 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO197 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO198 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO199 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |

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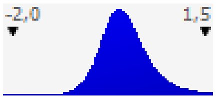
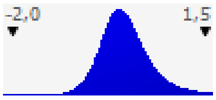
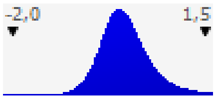
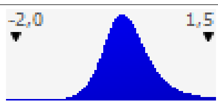
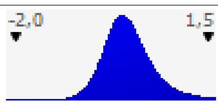
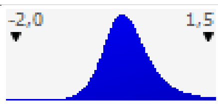
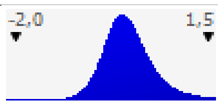
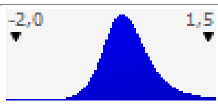
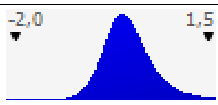
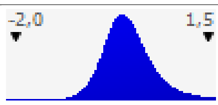
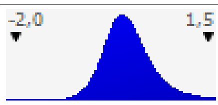
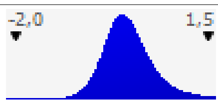
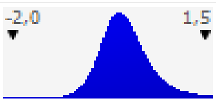
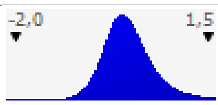
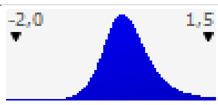
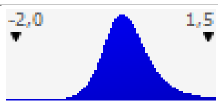
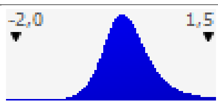
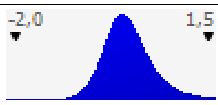
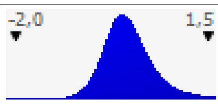
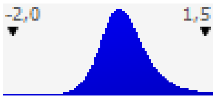
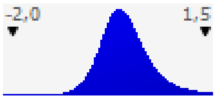
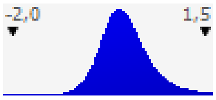
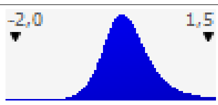
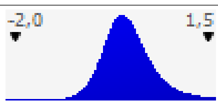
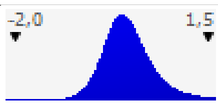
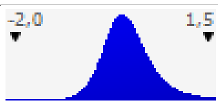
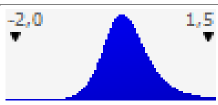
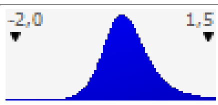
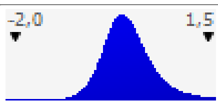
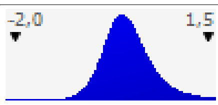
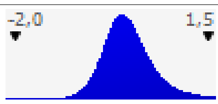
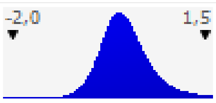
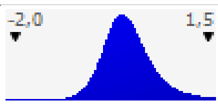
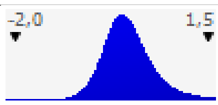
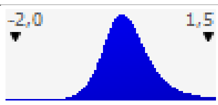
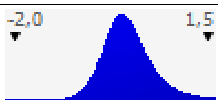
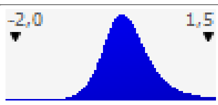
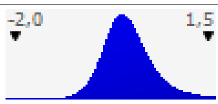
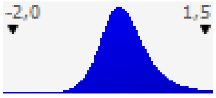
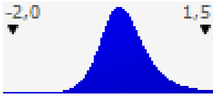
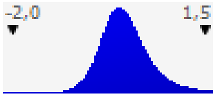
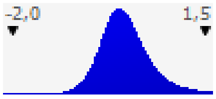
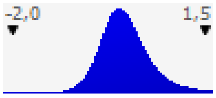
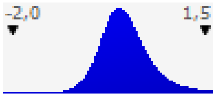
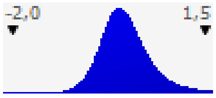
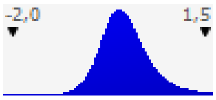
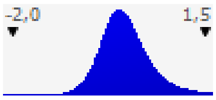
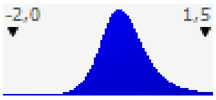
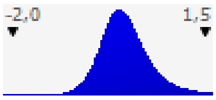
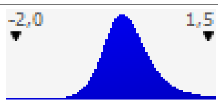
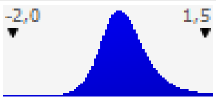
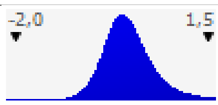
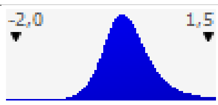
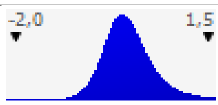
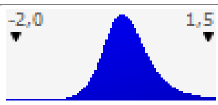
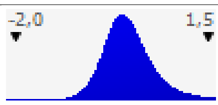
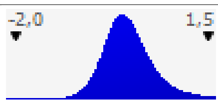
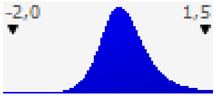
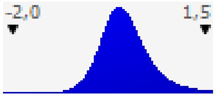
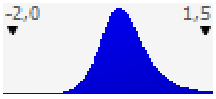
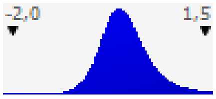
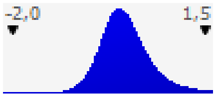
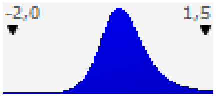
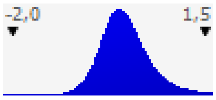
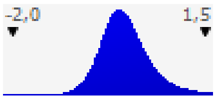
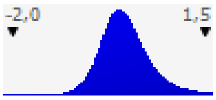
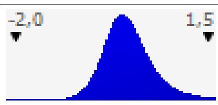
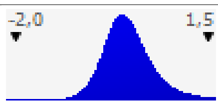
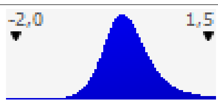
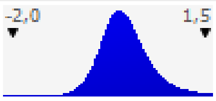
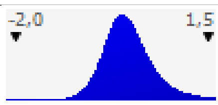
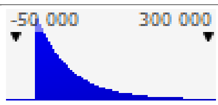
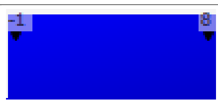
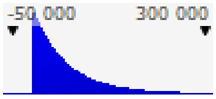
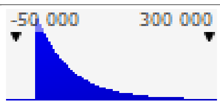
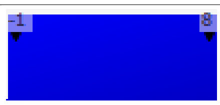
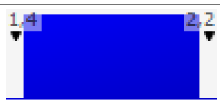
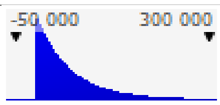
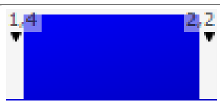
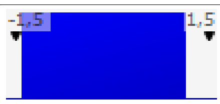
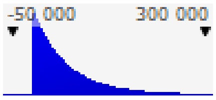
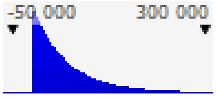
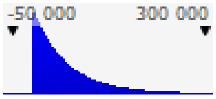
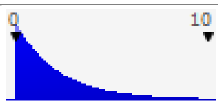
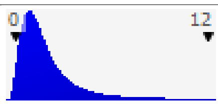
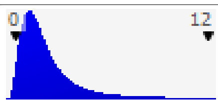
|---|---|---|---|---|---|---|---|
| | Euro Growth | AO200 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO201 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO202 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO203 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO204 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO205 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO206 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO207 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO208 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO209 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO210 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO211 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO212 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO213 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO214 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO215 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO216 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO217 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO218 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |

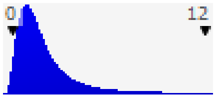
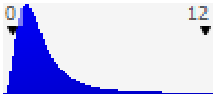
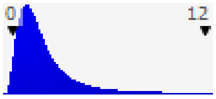
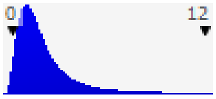
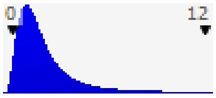
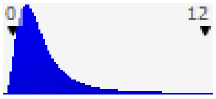
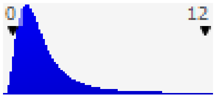
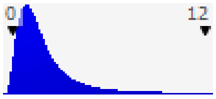
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Euro Growth | AO219 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO220 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO221 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO222 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO223 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO224 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO225 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO226 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO227 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO228 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO229 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO230 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO231 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO232 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO233 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO234 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO235 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO236 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO237 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |

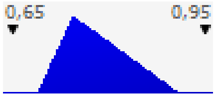
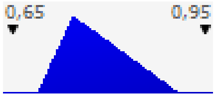
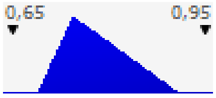
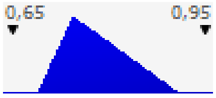
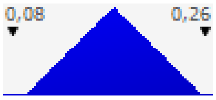
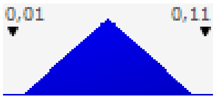
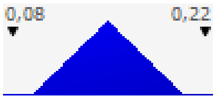
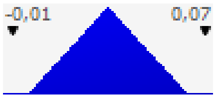
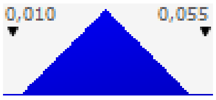
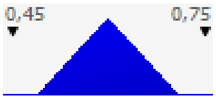
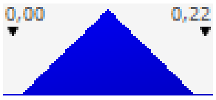
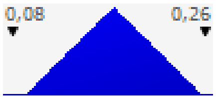
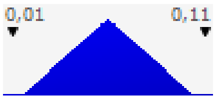
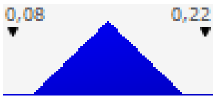
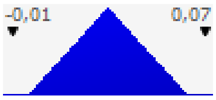
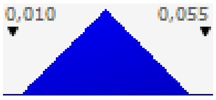
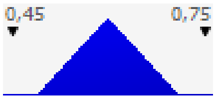
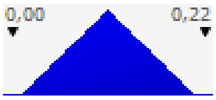
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Euro Growth | AO238 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO239 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO240 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO241 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO242 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO243 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO244 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO245 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO246 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO247 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO248 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO249 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO250 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO251 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO252 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO253 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO254 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO255 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO256 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |

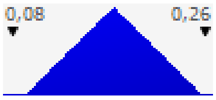
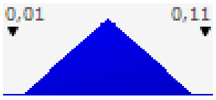
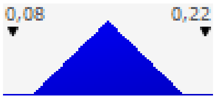
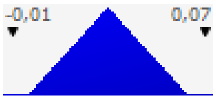
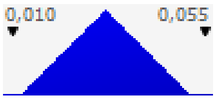
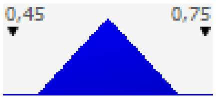
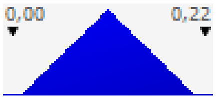
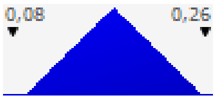
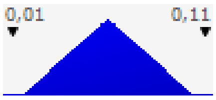
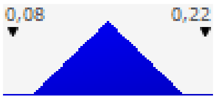
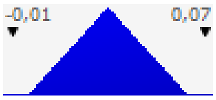
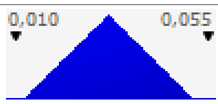
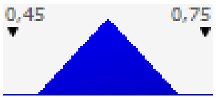
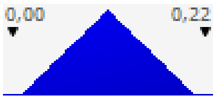
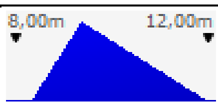
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Euro Growth | AO257 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO258 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO259 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO260 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO261 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO262 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO263 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO264 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO265 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO266 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO267 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO268 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO269 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Euro Growth | AO270 |  | RiskLoglogistic(-1,7495;1,7513;7,7671;RiskName("Euro Growth")) | -1,7495 | 0,050479 | +∞ |
| | Elect Growth | AO289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| | Low Scrap Price | AO301 |  | RiskUniform(1,46667;2,13333;RiskName("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AO302 |  | RiskUniform(1,67222;2,22778;RiskName("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Scrap | AP7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| | Elect Growth | AP289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Low Scrap Price | AP301 |   | RiskUniform(1,46667;2,13333;RiskName("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AP302 |   | RiskUniform(1,67222;2,22778;RiskName("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Repo2017 | AP332 |   | RiskUniform(-1,2917;1,0417;RiskName("Repo2017")) | -1,2917 | -0,125 | 1,0417 |
| | Scrap | AQ7 |   | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| | Elect Growth | AQ289 |   | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| | Low Scrap Price | AQ301 |   | RiskUniform(1,46667;2,13333;RiskName("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AQ302 |   | RiskUniform(1,67222;2,22778;RiskName("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | RepoYearly | AQ328 |   | RiskUniform(-1,2917;1,0417;RiskName("RepoYearly")) | -1,2917 | -0,125 | 1,0417 |
| | Repo2018 | AQ332 |   | RiskUniform(-1,2917;1,0417;RiskName("Repo2018")) | -1,2917 | -0,125 | 1,0417 |
| | Scrap | AR7 |   | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| | Elect Growth | AR289 |   | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| | Low Scrap Price | AR301 |   | RiskUniform(1,46667;2,13333;RiskName("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AR302 |   | RiskUniform(1,67222;2,22778;RiskName("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Repo2019 | AR332 |   | RiskUniform(-1,2917;1,0417;RiskName("Repo2019")) | -1,2917 | -0,125 | 1,0417 |
| | Scrap | AS7 |   | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| | Elect Growth | AS289 |   | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| | Low Scrap Price | AS301 |   | RiskUniform(1,46667;2,13333;RiskName("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| | Scrap Proce High | AS302 |   | RiskUniform(1,67222;2,22778;RiskName("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| | Repo2020 | AS332 |   | RiskUniform(-1,2917;1,0417;RiskName("Repo2020")) | -1,2917 | -0,125 | 1,0417 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Scrap | AT7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| Elect Growth | AT289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| Low Scrap Price | AT301 |  | RiskUniform(1,46667;2,13333;RiskName ("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| Scrap Proce High | AT302 |  | RiskUniform(1,67222;2,22778;RiskName ("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| Repo2021 | AT332 |  | RiskUniform(-1,2917;1,0417;RiskName("Repo2021")) | -1,2917 | -0,125 | 1,0417 |
| Scrap | AU7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| Elect Growth | AU289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| Low Scrap Price | AU301 |  | RiskUniform(1,46667;2,13333;RiskName ("Low Scrap Price")) | 1,46667 | 1,8 | 2,13333 |
| Scrap Proce High | AU302 |  | RiskUniform(1,67222;2,22778;RiskName ("Scrap Proce High")) | 1,67222 | 1,95 | 2,22778 |
| Repo2022 | AU332 |  | RiskUniform(-1,2917;1,0417;RiskName("Repo2022")) | -1,2917 | -0,125 | 1,0417 |
| Scrap | AV7 |  | RiskExpon(55468;RiskName("Scrap")) | 0 | 55468 | +∞ |
| Elect Growth | AV289 |  | RiskUniform(-0,86699;7,9851;RiskName("Elect Growth")) | -0,86699 | 3,559055 | 7,9851 |
| Repo2023 | AV332 |  | RiskUniform(-1,2917;1,0417;RiskName("Repo2023")) | -1,2917 | -0,125 | 1,0417 |
| Repo2024 | AW332 |  | RiskUniform(-1,2917;1,0417;RiskName("Repo2024")) | -1,2917 | -0,125 | 1,0417 |
| Repo2025 | AX332 |  | RiskUniform(-1,2917;1,0417;RiskName("Repo2025")) | -1,2917 | -0,125 | 1,0417 |
| Repo2026 | AY332 |  | RiskUniform(-1,2917;1,0417;RiskName("Repo2026")) | -1,2917 | -0,125 | 1,0417 |
| historical scrap price | BG306 |  | RiskChiSq(2;RiskShift(0,42);RiskName("historical scrap price")) | 0,42 | 2,42 | +∞ |
| historical scrap price | BG309 |  | RiskLoglogistic(0,20481;1,6089;2,3337;RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| historical scrap price | BH309 |  | RiskLoglogistic(0,20481;1,6089;2,3337;RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | historical scrap price | BI309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| | historical scrap price | BJ309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| | historical scrap price | BK309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| | historical scrap price | BL309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| | historical scrap price | BM309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| | historical scrap price | BN309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| | historical scrap price | BO309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| | historical scrap price | BP309 |  | RiskLoglogistic(0,20481;1,6089;2,3337; RiskName("historical scrap price")) | 0,20481 | 2,426494 | +∞ |
| Category: 2016 | | | | | | | |
| | 2016 / 2017 | AQ320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2018 | AR320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2019 | AS320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2020 | AT320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2026 | AU320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2022 | AV320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2023 | AW320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2024 | AX320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2025 | AY320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| | 2016 / 2026 | AZ320 | | RiskDiscrete($I$312:$K$312;$I$314:$K$314) | n/a | n/a | n/a |
| Category: Efficiency | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Efficiency / Min Efficiency | J29 |   | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Efficiency / Most Likely Efficiency | K29 |   | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Efficiency / Maximum Efficiency | L29 |   | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| | Efficiency / 2000 | M29 |   | RiskTriang($J$28;$K$28;$L$28) | 0,7 | 0,783333 | 0,9 |
| Category: Factor | | | | | | | |
| | Factor / Min Efficiency | J42 |   | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor / Min Efficiency | J45 |   | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor / Min Efficiency | J51 |   | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor / Min Efficiency | J54 |   | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor / Min Efficiency | J61 |   | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor / Min Efficiency | J64 |   | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor / Min Efficiency | J71 |   | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Factor / Most Likely Efficiency | K42 |   | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor / Most Likely Efficiency | K45 |   | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor / Most Likely Efficiency | K51 |   | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor / Most Likely Efficiency | K54 |   | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor / Most Likely Efficiency | K61 |   | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor / Most Likely Efficiency | K64 |   | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor / Most Likely Efficiency | K71 |   | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Factor / Maximum Efficiency | L42 |  | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor / Maximum Efficiency | L45 |  | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor / Maximum Efficiency | L51 |  | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor / Maximum Efficiency | L54 |  | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor / Maximum Efficiency | L61 |  | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor / Maximum Efficiency | L64 |  | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor / Maximum Efficiency | L71 |  | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| | Factor / 2000 | M42 |  | RiskTriang($C$53;$E$53;$D$53) | 0,1 | 0,175 | 0,25 |
| | Factor / 2000 | M45 |  | RiskTriang($C$54;$E$54;$D$54) | 0,02 | 0,06 | 0,1 |
| | Factor / 2000 | M51 |  | RiskTriang($C$56;$E$56;$D$56) | 0,1 | 0,15 | 0,2 |
| | Factor / 2000 | M54 |  | RiskTriang($C$57;$E$57;$D$57) | 0 | 0,03 | 0,06 |
| | Factor / 2000 | M61 |  | RiskTriang($C$61;$E$61;$D$61) | 0,014 | 0,032 | 0,05 |
| | Factor / 2000 | M64 |  | RiskTriang($C$62;$E$62;$D$62) | 0,5 | 0,6 | 0,7 |
| | Factor / 2000 | M71 |  | RiskTriang($C$66;$E$66;$D$66) | 0,02 | 0,11 | 0,2 |
| Category: FCI Dist | | | | | | | |
| | FCI Dist / Min | D26 |  | RiskTriang(D25;E25;F25) | R8 498 8 10,00 | R9 915 2 78,00 | R11 803 90 0,00 |
| Category: Yearly Change | | | | | | | |
| | Yearly Change / P | AQ317 | | RiskDiscrete($I$312:$K$312;$I$314:$K$ 314) | n/a | n/a | n/a |

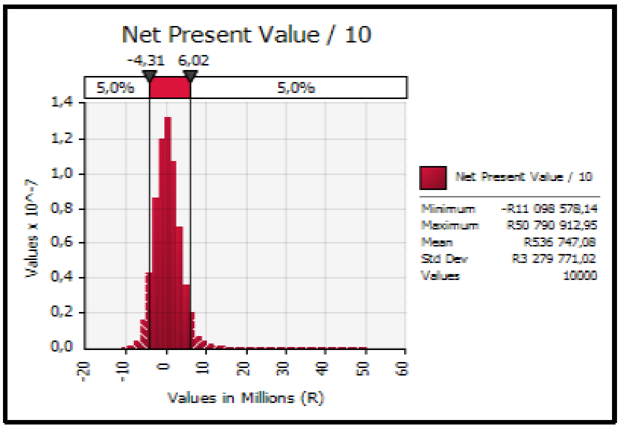
# Appendix D

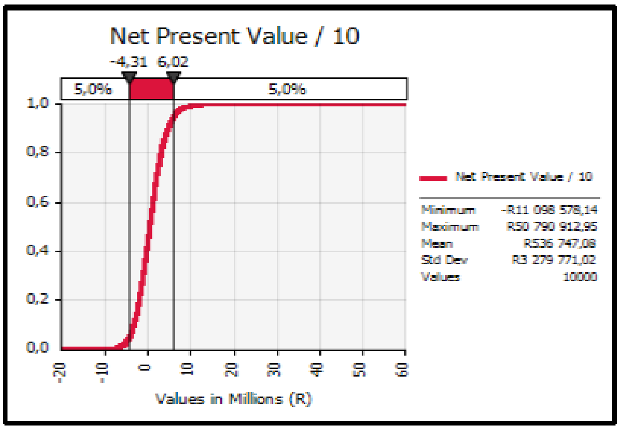
# Simulation Results

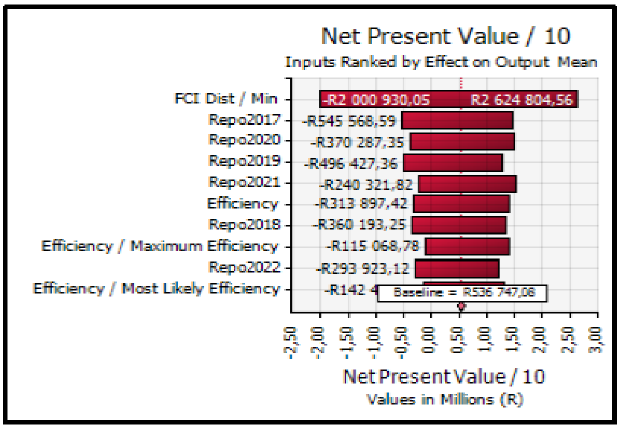
## @RISK Output Report for Net Present Value / 10

**Performed By:** Wilhelm
**Date:** 02 August 2016 12:53:22 AM

130% Fixed Profit Margin




**Simulation Summary Information**

| | |
|---|---|
| Workbook Name | Final Feasibility Model Post Crash.xlsx |
| Number of Simulations | 1 |
| Number of Iterations | 10000 |
| Number of Inputs | 733 |
| Number of Outputs | 1 |
| Sampling Type | Latin Hypercube |
| Simulation Start Time | 2016-08-02 00:26 |
| Simulation Duration | 00:01:03 |
| Random # Generator | Mersenne Twister |
| Random Seed | 1401835425 |

**Summary Statistics for Net Present Value / 10**

| Statistics | | Percentile | |
|---|---|---|---|
| Minimum | -R 11 098 578,14 | 5% | -R 4 313 809,57 |
| Maximum | R 50 790 912,95 | 10% | -R 3 343 234,19 |
| Mean | R 536 747,08 | 15% | -R 2 643 708,44 |
| Std Dev | R 3 279 771,02 | 20% | -R 2 099 564,40 |
| Variance | 1,07569E+13 | 25% | -R 1 655 210,22 |
| Skewness | 1,079588137 | 30% | -R 1 239 367,56 |
| Kurtosis | 12,12464503 | 35% | -R 802 271,20 |
| Median | R 353 501,11 | 40% | -R 398 257,68 |
| Mode | R 111 727,07 | 45% | R 5 532,36 |
| Left X | -R 4 313 809,57 | 50% | R 353 501,11 |
| Left P | 5% | 55% | R 737 404,43 |
| Right X | R 6 019 254,10 | 60% | R 1 133 331,64 |
| Right P | 95% | 65% | R 1 529 796,41 |
| Diff X | R 10 333 063,68 | 70% | R 1 948 368,66 |
| Diff P | 90% | 75% | R 2 475 666,32 |
| #Errors | 0 | 80% | R 2 995 979,55 |
| Filter Min | Off | 85% | R 3 664 407,43 |
| Filter Max | Off | 90% | R 4 565 640,12 |
| #Filtered | 0 | 95% | R 6 019 254,10 |

**Change in Output Statistic for Net Present Value / 10**

| Rank | Name | Lower | Upper |
|---|---|---|---|
| 1 | FCI Dist / Min | -R 2 000 930,05 | R 2 624 804,56 |
| 2 | Repo2017 | -R 545 568,59 | R 1 469 682,57 |
| 3 | Repo2020 | -R 370 287,35 | R 1 500 012,56 |
| 4 | Repo2019 | -R 496 427,36 | R 1 294 067,08 |
| 5 | Repo2021 | -R 240 321,82 | R 1 533 575,76 |
| 6 | Efficiency | -R 313 897,42 | R 1 389 601,73 |
| 7 | Repo2018 | -R 360 193,25 | R 1 342 169,49 |
| 8 | Efficiency / Maximum | -R 115 068,78 | R 1 391 750,71 |
| 9 | Repo2022 | -R 293 923,12 | R 1 203 784,70 |
| 10 | Efficiency / Most Likel | -R 142 439,59 | R 1 325 383,57 |

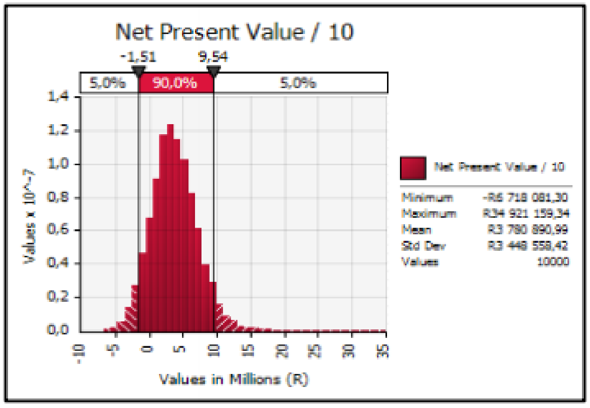
**Figure D.1:** Complete Simulation Results with 130% Fixed Profit Margin

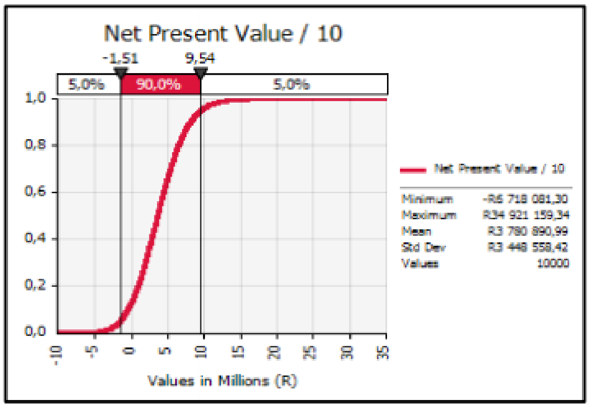
## @RISK Output Report for Net Present Value / 10

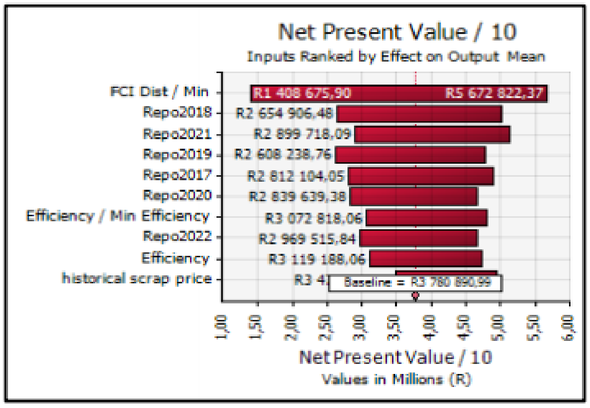
**Performed By:** Wilhelm

**Date:** 31 August 2016 11:23:38 PM

140% Fixed Profit Margin




| Simulation Summary Information | |
|---|---|
| Workbook Name | 140.xlsx |
| Number of Simulations | 1 |
| Number of Iterations | 10000 |
| Number of Inputs | 733 |
| Number of Outputs | 1 |
| Sampling Type | Latin Hypercube |
| Simulation Start Time | 2016-08-02 00:55 |
| Simulation Duration | 00:00:59 |
| Random # Generator | Mersenne Twister |
| Random Seed | 1972679777 |

**Summary Statistics for Net Present Value / 10**

| Statistics | | Percentile | |
|---|---|---|---|
| Minimum | -R 6 718 081,30 | 5% | -R 1 511 151,97 |
| Maximum | R 34 921 159,34 | 10% | -R 443 567,06 |
| Mean | R 3 780 890,99 | 15% | R 345 905,46 |
| Std Dev | R 3 448 558,42 | 20% | R 943 083,20 |
| Variance | 1,18926E+13 | 25% | R 1 474 957,55 |
| Skewness | 0,651546958 | 30% | R 1 916 257,07 |
| Kurtosis | 5,711418308 | 35% | R 2 343 074,04 |
| Median | R 3 582 358,45 | 40% | R 2 794 640,92 |
| Mode | R 3 619 103,58 | 45% | R 3 205 679,99 |
| Left X | -R 1 511 151,97 | 50% | R 3 582 358,45 |
| Left P | 5% | 55% | R 4 011 439,77 |
| Right X | R 9 537 413,11 | 60% | R 4 429 176,65 |
| Right P | 95% | 65% | R 4 891 211,00 |
| Diff X | R 11 048 565,08 | 70% | R 5 375 961,38 |
| Diff P | 90% | 75% | R 5 894 861,02 |
| #Errors | 0 | 80% | R 6 485 482,56 |
| Filter Min | Off | 85% | R 7 186 338,97 |
| Filter Max | Off | 90% | R 8 105 708,12 |
| #Filtered | 0 | 95% | R 9 537 413,11 |

**Change in Output Statistic for Net Present Value / 10**

| Rank | Name | Lower | Upper |
|---|---|---|---|
| 1 | FCI Dist / Min | R 1 408 675,90 | R 5 672 822,37 |
| 2 | Repo2018 | R 2 654 906,48 | R 5 005 402,17 |
| 3 | Repo2021 | R 2 899 718,09 | R 5 136 104,61 |
| 4 | Repo2019 | R 2 608 238,76 | R 4 769 037,77 |
| 5 | Repo2017 | R 2 812 104,05 | R 4 904 024,02 |
| 6 | Repo2020 | R 2 839 639,38 | R 4 657 500,59 |
| 7 | Efficiency / Min Effi | R 3 072 818,06 | R 4 813 350,32 |
| 8 | Repo2022 | R 2 969 515,84 | R 4 654 891,28 |
| 9 | Efficiency | R 3 119 188,06 | R 4 739 432,05 |
| 10 | historical scrap pric | R 3 477 320,67 | R 4 949 804,96 |

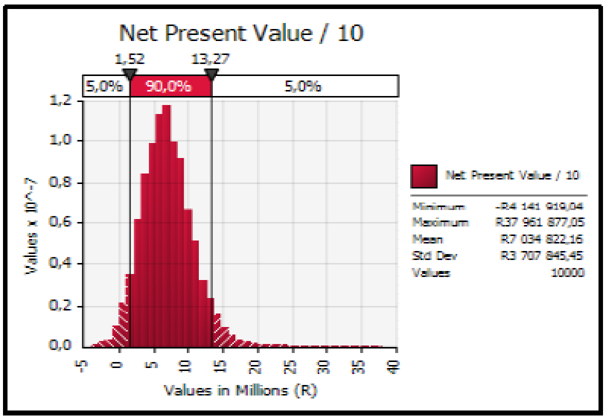
**Figure D.2:** Complete Simulation Results with 140% Fixed Profit Margin

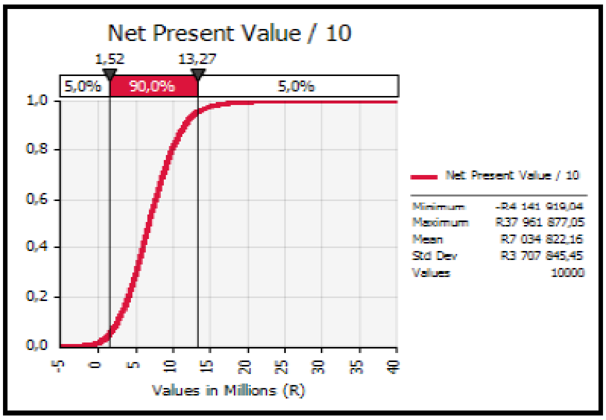
## @RISK Output Report for Net Present Value / 10

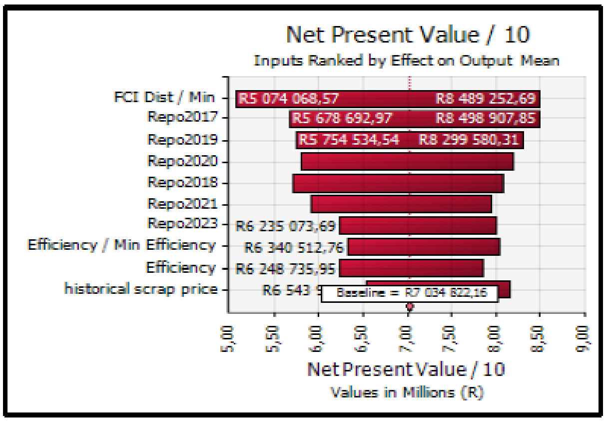
**Performed By:** Wilhelm

**Date:** 02 August 2016 01:00:57 PM

150% Fixed Profit Margin




| Simulation Summary Information | |
|---|---|
| Workbook Name | 150.xlsx |
| Number of Simulations | 1 |
| Number of Iterations | 10000 |
| Number of Inputs | 733 |
| Number of Outputs | 1 |
| Sampling Type | Latin Hypercube |
| Simulation Start Time | 2016-08-02 01:13 |
| Simulation Duration | 00:01:01 |
| Random # Generator | Mersenne Twister |
| Random Seed | 2057556969 |

**Summary Statistics for Net Present Value / 10**

| Statistics | | Percentile | |
|---|---|---|---|
| Minimum | -R 4 141 919,04 | 5% | R 1 519 504,34 |
| Maximum | R 37 961 877,05 | 10% | R 2 586 028,37 |
| Mean | R 7 034 822,16 | 15% | R 3 357 366,86 |
| Std Dev | R 3 707 845,45 | 20% | R 3 959 869,72 |
| Variance | 1,37481E+13 | 25% | R 4 514 877,43 |
| Skewness | 0,766243408 | 30% | R 5 025 037,75 |
| Kurtosis | 5,865526199 | 35% | R 5 493 619,18 |
| Median | R 6 786 474,00 | 40% | R 5 917 742,34 |
| Mode | R 5 882 022,94 | 45% | R 6 375 054,34 |
| Left X | R 1 519 504,34 | 50% | R 6 786 474,00 |
| Left P | 5% | 55% | R 7 208 837,68 |
| Right X | R 13 266 302,61 | 60% | R 7 674 886,60 |
| Right P | 95% | 65% | R 8 194 914,27 |
| Diff X | R 11 746 798,27 | 70% | R 8 679 162,12 |
| Diff P | 90% | 75% | R 9 237 139,47 |
| #Errors | 0 | 80% | R 9 865 032,35 |
| Filter Min | Off | 85% | R 10 658 853,17 |
| Filter Max | Off | 90% | R 11 628 521,85 |
| #Filtered | 0 | 95% | R 13 266 302,61 |

**Change in Output Statistic for Net Present Value / 10**

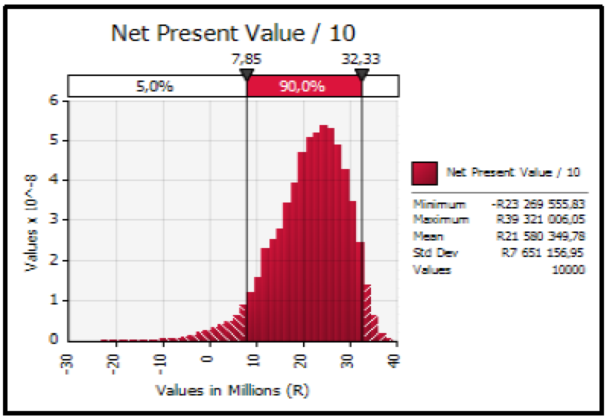
| Rank | Name | Lower | Upper |
|---|---|---|---|
| 1 | FCI Dist / Min | R 5 074 068,57 | R 8 489 252,69 |
| 2 | Repo2017 | R 5 678 692,97 | R 8 498 907,85 |
| 3 | Repo2019 | R 5 754 534,54 | R 8 299 580,31 |
| 4 | Repo2020 | R 5 800 107,22 | R 8 191 811,18 |
| 5 | Repo2018 | R 5 720 169,04 | R 8 082 601,28 |
| 6 | Repo2021 | R 5 914 484,79 | R 7 942 000,70 |
| 7 | Repo2023 | R 6 235 073,69 | R 7 997 803,40 |
| 8 | Efficiency / Min Efficien | R 6 340 512,76 | R 8 046 273,50 |
| 9 | Efficiency | R 6 248 735,95 | R 7 862 822,79 |
| 10 | historical scrap price | R 6 543 987,75 | R 8 150 670,60 |

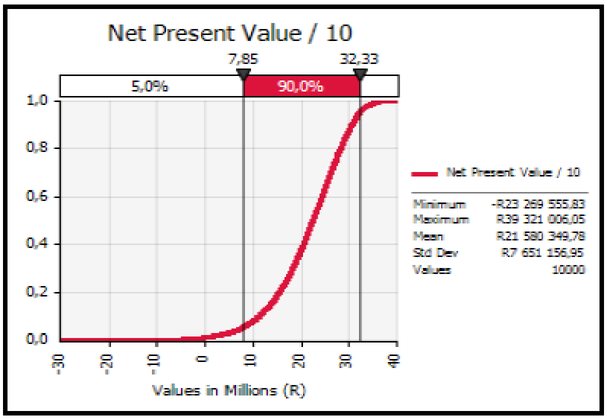
**Figure D.3:** Complete Simulation Results with 150% Fixed Profit Margin

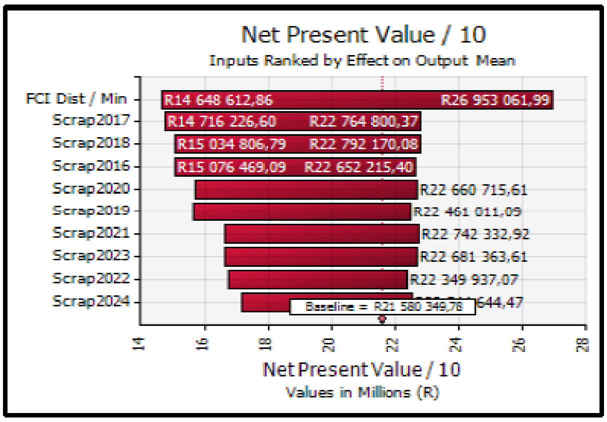
## @RISK Output Report for Net Present Value / 10

**Performed By:** Wilhelm

**Date:** 02 August 2016 07:03:46 PM **Selling Price Fixed at R1000**




**Simulation Summary Information**

| | |
|---|---|
| Workbook Name | Fixed.xlsx |
| Number of Simulations | 1 |
| Number of Iterations | 10000 |
| Number of Inputs | 133 |
| Number of Outputs | 1 |
| Sampling Type | Latin Hypercube |
| Simulation Start Time | 2016-08-02 19:01 |
| Simulation Duration | 00:00:34 |
| Random # Generator | Mersenne Twister |
| Random Seed | 1387784362 |

**Summary Statistics for Net Present Value / 10**

| Statistics | | Percentile | |
|---|---|---|---|
| Minimum | -R 23 269 555,83 | 5% | R 7 854 152,05 |
| Maximum | R 39 321 006,05 | 10% | R 11 403 679,27 |
| Mean | R 21 580 349,78 | 15% | R 13 530 780,60 |
| Std Dev | R 7 651 156,95 | 20% | R 15 454 932,55 |
| Variance | 5,85402E+13 | 25% | R 16 945 916,09 |
| Skewness | -0,703786222 | 30% | R 18 308 060,34 |
| Kurtosis | 3,631866971 | 35% | R 19 471 571,48 |
| Median | R 22 495 866,80 | 40% | R 20 499 861,94 |
| Mode | R 20 999 732,59 | 45% | R 21 481 292,13 |
| Left X | R 7 854 152,05 | 50% | R 22 495 866,80 |
| Left P | 5% | 55% | R 23 457 612,95 |
| Right X | R 32 331 652,17 | 60% | R 24 402 382,10 |
| Right P | 95% | 65% | R 25 306 064,94 |
| Diff X | R 24 477 500,12 | 70% | R 26 201 474,94 |
| Diff P | 90% | 75% | R 27 223 863,52 |
| #Errors | 0 | 80% | R 28 263 855,81 |
| Filter Min | Off | 85% | R 29 400 320,62 |
| Filter Max | Off | 90% | R 30 653 948,49 |
| #Filtered | 0 | 95% | R 32 331 652,17 |

**Change in Output Statistic for Net Present Value / 10**

| Rank | Name | Lower | Upper |
|---|---|---|---|
| 1 | FCI Dist / Min | R 14 648 612,86 | R 26 953 061,99 |
| 2 | Scrap2017 | R 14 716 226,60 | R 22 764 800,37 |
| 3 | Scrap2018 | R 15 034 806,79 | R 22 792 170,08 |
| 4 | Scrap2016 | R 15 076 469,09 | R 22 652 215,40 |
| 5 | Scrap2020 | R 15 661 917,69 | R 22 660 715,61 |
| 6 | Scrap2019 | R 15 639 829,44 | R 22 461 011,09 |
| 7 | Scrap2021 | R 16 608 700,45 | R 22 742 332,92 |
| 8 | Scrap2023 | R 16 633 840,46 | R 22 681 363,61 |
| 9 | Scrap2022 | R 16 751 743,23 | R 22 349 937,07 |
| 10 | Scrap2024 | R 17 147 617,18 | R 22 544 644,47 |

**Figure D.4:** Complete Simulation Results with Fixed Selling Price at R1000 per Casting

# Appendix E

# Equipment Quotations

## E.1 Titancast-700P-VAR (Linn High Therm)

Heinrich-Hertz-Platz 1
92275 Eschenfelden / Germany
Phone: +49 9665 9140-0
Fax: +49 9665 1720
info@linn.de
**www.linn.de**

Stellenbosch University
50 Fynbos
7600 Stellenbosch
**South Africa**

2016-05-30
Zi

**QUOTATION NO. 111067.1**

Dear Sirs,

We thank you very much for your enquiry. Subject to our attached General Terms of Sales and Delivery (green/white), which are an essential part of this quotation and contain the right of property, we offer as follows:

**1 piece** **High frequency vacuum centrifugal casting unit for Titanium casting production**

**type TITANCAST-700P-VAC**

for casting of precious and base metals as well as their alloys

Technical specifications:

| | |
|---|---|
| size of cuvette max. diameter | app. 140 mm, length max. 200 mm |
| melting power | app. 7,0 kW |
| generator frequency | app. 0,8 – 1 MHz |
| casting revolutions max. | 400 U/min |
| casting time | variable from 0 - 60 seconds – will be adjusted firmly during installation |
| input power incl. vacuum system | app. 19 kVA |
| vacuum idle motion max. | $5 \times 10^{-3}$ mbar |
| vacuum melting max. | $8 \times 10^{-2}$ mbar |

| | |
|---|---|
| voltage supply | 400 V -10%/+5%; 50/60 Hz, 3 phase |
| dimensions casting unit | app. 920 x 900 x 1600 mm (wxdxh) |
| weight casting system | app. 470 kg |
| dimensions vacuum pump stand system | app. 1100 x 540 x 1100 mm (wxdxh) |
| weight vacuum pump stand system | app. 250 kg |
| cooling water | app. 8 l/min at 3-5 bar, max. 25°C |

**General**

With this casting system you dispose of a modern casting unit which enables you to cast noble metals as Platinum, Gold, Palladium and Silver – but also most of the other metals. You can either work under vacuum with the closed casting arm or under protective gas flushing with slight overpressure and normal atmosphere.

The system is works after the centrifugal casting principal. The material is melted with the help of high frequency in a ceramic – or graphite crucible within short term and poured into the prepared cuvettes after reaching the casting temperature by controlled centrifugal power. Depending on the size of the casting part as well as the handled material and its amount the casting revolution and the run up time can be indivually adjusted at hands of a diagram for each cuvette.

The unbalance of the casting arm can be easily removed with the help of adjustable counterweights. The temperature can be watched with a spectral pyrometer with adjustable emission factor during the complete melting process (option).

The system consist of a noise suppressioned high frequency generator with an induction coil power of approx. kW and an operating frequency of approx. 0,8 bis 1,1 MHz which is mounted together with the induction melting furnace working under athmosphere and vacuum respectively or vacuum with protective gas flushing and centrifugal casting device in a compact, double lacquered steel housing. The space required is 3 m² incl. pump stand system

The casting are is placed into a tank made of stainless steel. This tank enables a clean recovery of squirted material.

## Control of the machine:

1. Hardware / HMI

-The operation is done over a coloured touch panel 7" with 10 integrated function keys and integrated PLC function.
-Decentralized control blocks are used for the control of the machine functions.
-All inputs and outputs of the sensors and actuators are galvanically isolated and are protectively connected to MF/HF with the decentralized control unit.
-Process data and process parameters can be read out over an USB interface.
-An emergency switch which is well accessible gives additional safety during operation.

2. Scope of functions

-Simple user operation through self-explanatory menu navigation and navigated program flows.
-Optical visualisation of program flow of the respective work steps, program inform over the current status of the machine.
-Integrated recipe administration for melting programs (number depending on memory).
-Compiled melting programmes can be saved easily on a USB stick and implement in further machines of the same types, without having to compile it new.
-Safety supervision from various functions with clear text and acoustic alarm emission, for example cooling water temperature, cooling water flow, cover and door locking, generator current(power).
-Optical and accoustic signalization in case of failures and at the end of the casting process.
-Recording of all alarms and faults with date and time stamp.
-User language selectable (German, English = standard, others on request against surcharge).
- User level locked interface (manufacturer, administrator, operator)

3. Hand mode

-Free adjustable process parameters in order to optimize processes and compiled melting programmes.
-Status display of hardware inputs and outputs.

4. Optional, on request:

-Option: Optical pyrometer and controller operation over PID controller.
-Optional process data acquisition of generator power and melting temperature
-Ethernet interface for integration in a customer network.

| | |
|---|---|
| safety switch | Magnetic cover locking during casting process, as well as automatic power switch off when opening the cover during the melting process. |
| program functions | Atmosphere, vacuum or pre-vacuum with following protective gas flushing up to max. 0,4 bar.<br>(upon request up to 2 bar against surcharge) |

**Melting – and casting atmosphere**

As melting – and casting atmosphere respectively can be chosen:
- normal atmosphere
- under gas flushing
- under vacuum
- under vacuum with gas flushing

**Casting athmosphere**

The casting arm is designed as vacuum – and gastight casting chamber. With the vacuum casting arm it is possible to work under air atmosphere as well as under vacuum or vacuum with following protective gas flushing when there is light overpressure. Regarding to alloys with a high vapour pressure or easily oxidizing alloys the above described working method habit is of advantage.

The casting atmosphere is adjusted on the control panel with the selection mode switch. On the flow meter which is installed on the control panel at everytime the induced gas amount into the casting arm can be checked. As protectie gas we recommend Ar or forming gas with max. 5 % $H_2$.

**Vacuum**

During the melting a vacuum of max. approx. 8 x $10^{-2}$ mbar is reached. In idle mode without cuvettes, without melt and after the pouring the maximum vacuum of max. approx. 5 x $10^{-3}$ mbar is reached. The vacuum is effected by a roots pump stand system with a 360 m³/h roots pump and corresponding pre – pumps. With a digital vacuum display and a limit value contact the vacuum can be watched over the complete casting cycle. The min. vacuum display is 1 x $10^{-3}$ mbar.

The pump down time up to a vacuum of approx. $10^{-2}$ mbar is for an empty, dry vacuum arm approx. 30 seconds regarding to warm vacuum pump without gas ballast.

In the casting arm a viewing glass made of quartz glass is installed which enables watching of the metal during the complete melting process. Through the viewing glass at the same time the temperature of the metal can be measured with the help of the spectral pyrometer (option). On the lower side of the casting arm a quartz glass crucible is situated which limits the inner room of the casting arm against the atmosphere. The connection quartz glass crucible – castin arm is guaranteed by a temperature resistant sealing. On the housing of the casting arm for cooling of the housing cooling rips are installed. For better cooling of the casting arm for its housing an Aluminium alloy has been used.

## Drive

The casting arm is operated by a three phase current servo motor which is controlled by a frequency inverter. The advantages of the used motor are as follows:

- no electrical wear parts are used and so
- the motor is maintenance free,
- it has a high accelaration capacity because the rotor has a low moment of inertia due to high power density.
- it has a high velocity moments also in upper revolution range because it has no commutation limit curve.
- he has a high torque over the complete torque area, also in stand still.

The torque will be transported with the help of gear belt to the spindle of the casting arm.

## Safety switching

A solenoid cover locking supervises / locks the cover the casting system during the melting – and casting process. Through this safety device it is guaranteed that the cover of the casting room during the casting process (as long as the casting arm rotates) is not opened by mistake and that therefore will be injuries.
For safety reasons the melting program can only be started when the cover of the casting arm is closed. As soon as the cover is opened during the melting process the melting program is automatically interrupted and the power of the system is switched off.
On the system safety devices are installed which switch off the power of the system and release a failure alarm as soon as the door is opened. Therefore it is not possible to run the unit with open doors.
The inner temperature supervision avoids that the system is overloaded.

## Size of cuvettes

Cuvettes with a size of max. approx. 140 mm diameter and max. approx. 200 mm length and a weight of max. approx. 7 kg can be used. Of course furthermore the normal cuvettes sizes can be used with corresponding holders.

## Cooling water connection

With switch off automatic approx ca. 8 l/min. at min. 3 bar, max. 5 bar, regarding to a water temperature of max. 25°C. During use of de-ionized tube water max. hardening grade 6° German hardness, conductivity max. 200 µS/cm.

## Material insert amount depending upon crucible

| | | | |
|---|---|---|---|
| Titanium | up to 350 g | | |
| Platinum | approx. 600 g | New silver | approx. 1000 g |
| Palladium | approx. 1000 g | Bronze | approx. 1000 g |
| Gold | approx. 1200 g | Copper | approx. 1000 g |
| Silver | approx. 1000 g | Brass | approx. 1000 g |
| | | CrNi steel | approx. 800 g |

Basic equipment (included in system price)

| Quantity | Description |
|---|---|
| 2 pieces | hose clamps steel |
| 6 pieces | hose clamps steel |
| 1 tube | vacuum grease |
| 1 pieces | bulk E 27, 200 W |
| 2 pieces | neozed fuses 2 A |
| 3 pieces | neozed fuses 6 A |
| 3 pieces | neozed fuses 10 A |
| 3 pieces | neozed fuses 16 A |
| 3 pieces | neozed fuses 35 A |
| 2 pieces | fine fuses 0,8 A |
| 4 m | gas hose, 6 mm diameter |
| 10 m | water hose, 8 mm diameter |
| 1 piece | equalizing cotter 4 mm |
| 1 piece | equalizing cotter 7 mm |
| 1 piece | machine key |
| 6 pieces | graphite crucible SGV2-G |
| 6 pieces | ceramic crucible SKV2-LR-0 |
| 1 piece | quartz glass crucible SQV2-Q |

| | |
|---|---|
| 1 set | sealing |
| 1 set | distance plates |
| 1 piece | induction coil |
| 1 set | muffle inserts |

The furnace is designed according to machine guidelines, to low voltage guidelines and if there is a pressure or vacuum vessel also according to pressure vessel guidelines. Our product standard is EN-746.

**Price of described system** **€ 134.990,--**
**Art.-No. 108937** **==========**

**<u>Options</u>**

**Depending on the option(s), a larger control housing might be necessary. This will be discussed with you in case of order.**

**<u>Pyroscope type 217 R/A 800 - 2300 °C (Art.no. 100900)</u>**

Measuring range 800 - 2300°C measuring distance / measuring spot 160 mm / 3 mm with photoconductor and front optics, spectral range
0,85 - 1,1 um, digital display, 2 value indicators, variably adjustable

**for a price of** **€ 5.990,--**
**==========**

**<u>Circulation cooling unit RK-4 (Art.no. 100902)</u>**

Compact cooling water recooler with fully hermetical motor compressor and complete cooling water circulation. With water tank and circulation pump. The cooling capacity at a water temperature of +15°C and ambient temperature of +32°C is app. 2,4 kW; tank capacity 26 liters. The water connection is provided via plug in couplings 8 and 12 mm. The housing consists of electrolytically galvanized sheet steel and is powder coated, resistant to abrasion and scratches, water, dissolvers, cooling media or hydraulic oils. An electromechanical thermostat serves for temperature measurement.

**for a price of** **€ 3.850,--**
**==========**

**Pyrometer IS 210, 650-1800°C with G 400 (No. 106240)**

It serves for supervision and control of melting temperature via contactless temperature measuring. Temperature range: 650-1800°C including 2m connection cable. The emission grade can be adjusted over the hand terminal IMPAC HT 6000 interface KUI (optional). (other measuring ranges on request against surcharge)

**for a price of** **€ 2.620,--**
**==========**

**Connection cable for HT 6000 (104382)**

For connection of a HT 6000 to the service interface.

**for a price of** **€ 155,--**
**==========**

**Hand terminal IMPAC HT 6000 (104368)**

Parameterizing unit for adjustment of emission grade, response time, measuring range etc. on pyrometer.

**for a price of** **€ 816,--**
**========**

**Protective gas cleaning (109031)**

Cleaning of protective gas by a gas-cleaning cartridge. Oxygen and water vestiges are removed of the protective gas.

**for a price of** **€ 2.700,--**
**==========**

**Consumption material**

| | | | | |
|---|---|---|---|---|
| 10 pieces | graphite crucible SGV2-G | 102662 | € | 41,40/ piece |
| 20 pieces | ceramic crucible SKV2-LR-0 | 102683 | € | 71,70/ piece |
| 1 piece | quartz crucible SQV2-Q | 102757 | € | 597,00 |
| 1 piece | blue glass 110x110x3 mm | 100547 | € | 24,20 |
| 1 piece | quartz glass 85x4 mm | 100551 | € | 155,00 |
| 2 pieces | quartz crucible sealings 85x4 mm | 101621 | € | 14,60/ piece |
| 2 pieces | quartz disc sealings 75x4 mm | 101619 | € | 14,60/ piece |
| 1 piece | cover sealing 295 x 6 mm | 101624 | € | 30,50/ piece |

OFFER IS SUBJECT TO TECHNICAL CHANGES!

**Preliminary or Final Acceptance on the premises of Linn High Therm**

If you inquire a Preliminary- or Final Acceptance on our premises please let us know your requested test sequence so that we can give you a detailed quote.

Please note that this calculation is subject to latest, up-to-minute material prices. We reserve us the right to demand at time of contract conclusion a new determination of contract price due to possible prices increase in commodities, freights, taxes, duties, dues or in any other charges.

**ATTENTION: PLEASE NOTE THAT DUE TO THE TECHNICAL SPECIFICATONS OF THIS UNIT AN EXPORT LICENSE IS REQUIRED!!!**

| | |
|---|---|
| quotation validity: | This offer is valid until 31.07.2016. |
| price base: | unpacked, ex our works (All prices are in €.) |
| payment: | 35% down payment on receipt of order,<br>65% against irrevocable and confirmed<br>letter of credit through Sparkasse Nürnberg:<br>bank code 760 501 01<br>account-n°: 190 002 501<br>SWIFT: SSKNDE 77<br>L/C conditions: 65 % against presentation of shipping documents.<br>All L/C charges inside and outside of our country are for buyer's account. |
| delivery time: | app. 12 weeks after receipt of firm order, receipt of 35% down payment, receipt of clean, valid and acceptable L/C over 65% of the contract value and receipt of export license as well as clarification of all technical and commercial details (our indicated delivery time does not include delivery to customer). |
| warranty: | 1 year except for consumables and wear parts.<br>Warranty for RF-tubes, magnetrons or similar is<br>6 months, only (warranty of manufacturer) |
| not included: | Assembling and installation. This can be done by our company and will be charged against our valid service rates. |

Export control

We reserve the right to examine the quotation if at time of order following is missing or doubtful

- end user certificate
- confirmation of non military and non nuclear application

Please note that all contracts are subject to our general terms of sales and delivery and that other conditions cannot be accepted.

We should be pleased if our offer meets your requirements and remain,

Yours sincerely,

Jennifer Ziegler
Sales- and Export Department

Linn High Therm GmbH
Director of company: Horst Linn
HRB 3262 local court Amberg

# Appendix F

# Benchmark Components Machine Sheets

## F.1 Volume Removed per Machine Step of Benchmark Components

| Process Step | Scrap Volume ($cm^3$) | Scrap Weight (g) |
|---|---|---|
| 1.1 | 206.7 | 915.672 |
| 1.2 | 3.76 | 16.673 |
| 1.3 | 1.77 | 7.825 |
| 1.4 | 4.55 | 20.176 |
| 2.1 | 67.64 | 299.631 |
| 2.2 | 47.62 | 210.961 |
| 2.3 | 45.63 | 202.137 |
| 2.4 | 43.58 | 193.04 |
| 2.5 | 8.01 | 35.466 |
| 2.6 | 0.46 | 2.057 |
| 2.7 | 2.84 | 12.567 |
| Finishing 1 | 6.71 | 29.709 |
| Finishing 2 | 2.89 | 12.801 |
| Finishing 3 | 4.31 | 19.108 |
| Total | 124.14 | 1977.823 |

**Table F.1:** Banana-Brace Scrap Production per Process Step

| Process Step | Scrap Volume ($cm^3$) | Scrap Weight (g) |
|---|---|---|
| 1.1 | 625.71 | 2771.916 |
| 1.2 | 91.61 | 405.842 |
| 1.3 | 1.06 | 4.718 |
| 1.4 | 4.41 | 19.529 |
| 1.5 | 2.20 | 9.757 |
| 2.1 | 1331.70 | 5899.43 |
| 2.2 | 1290.14 | 5715.319 |
| 2.3 | 216.94 | 961.035 |
| 2.4 | 124.21 | 550.261 |
| 2.5 | 39.79 | 176.274 |
| 2.6 | 70.96 | 314.356 |
| Solids | | |
| 2 Plugs | 387.54 | 1716.80 |
| Left Support | 198.70 | 880.25 |
| Right Support | 96.53 | 427.606 |
| Total | 4 481.51 | 19 853.089 |

**Table F.2:** Intercostal Scrap Production per Process Step

| Process Step | Scrap Volume ($cm^3$) | Scrap Weight (g) |
|---|---|---|
| 1.1 | 33.97 | 150.503 |
| 1.2 | 607.37 | 2690.648 |
| 1.3 | 147.59 | 653.804 |
| 1.4 | 608.42 | 2695.296 |
| 1.5 | 229.49 | 1016.641 |
| 1.6 | 0.80 | 3.562 |
| 1.7 | 3.52 | 15.591 |
| 1.8 | 7.54 | 33.408 |
| 1.9 | 7.49 | 33.202 |
| 1.10 | 2.36 | 10.446 |
| 1.11 | 6.50 | 28.783 |
| 1.12 | 86.54 | 383.352 |
| 1.13 | 0.05 | 0.216 |
| 1.14 | 0.22 | 0.962 |
| 1.15 | 0.06 | 0.274 |
| 1.16 | 0.12 | 0.519 |
| 1.17 | 3.62 | 16.042 |
| 1.18 | 0.02 | 0.093 |
| 2.1 | 27.60 | 122.282 |
| 2.2 | 645.73 | 2860.587 |
| 2.3 | 392.57 | 1739.065 |
| 2.4 | 11.62 | 51.494 |
| 2.5 | 469.85 | 2081.433 |
| 2.6 | 245.10 | 1085.772 |
| 2.7 | 115.42 | 511.316 |
| 2.8 | 62.53 | 277.028 |
| 2.9 | 5.70 | 25.24 |
| 2.10 | 17.58 | 77.878 |
| 2.11 | 2.98 | 13.208 |
| 2.12 | 0.38 | 1.700 |
| 2.13 | 3.56 | 15.753 |
| 2.14 | 0.002 | 0.008 |
| 2.15 | 0.002 | 0.008 |
| 2.16 | 0.364 | 1.614 |
| 2.17 | 3.58 | 15.87 |
| Total | 3 750.25 | 16 613.593 |

**Table F.3:** Wing Riblet Scrap Production per Process Step

| Process Step | Scrap Volume ($cm^3$) | Scrap Weight (g) |
|---|---|---|
| 1.1 | 383.13 | 1697.269 |
| 1.2 | 0.82 | 3.631 |
| 1.3 | 1.41 | 6.256 |
| 1.4 | 1.98 | 8.767 |
| 1.5 | 2.17 | 9.605 |
| 1.6 | 0.12 | 0.524 |
| 1.7 | 0.88 | 3.877 |
| 1.8 | 0.54 | 2.383 |
| 1.9 | 1.03 | 4.542 |
| 1.10 | 0.83 | 3.694 |
| 1.11 | 0.18 | 0.792 |
| 1.12 | 0.90 | 3.977 |
| 1.13 | 0.21 | 0.934 |
| 1.14 | 0.10 | 0.447 |
| 1.15 | 0.04 | 0.198 |
| 1.16 | 0.05 | 0.221 |
| 2.1 | 53.84 | 238.530 |
| 2.2 | 0.5 | 2.199 |
| 2.3 | 0.67 | 2.981 |
| 2.4 | 0.33 | 1.453 |
| 2.5 | 0.54 | 2.399 |
| 2.6 | 0.06 | 0.258 |
| 2.7 | 0.08 | 0.335 |
| 2.8 | 0.07 | 0.308 |
| 2.9 | 32.08 | 142.096 |
| 2.10 | 0.74 | 3.288 |
| 2.11 | 1.16 | 5.120 |
| 2.12 | 15.66 | 69.352 |
| 2.13 | 1.35 | 5.966 |
| 2.14 | 0.06 | 0.258 |
| 2.15 | 0.12 | 0.537 |
| Total | 501.62 | 2 222.198 |

**Table F.4:** Knuckleduster Scrap Production per Process Step

# Appendix G

# Conference Papers

## G.1 IAMOT 2016 Paper

# A MANAGEMENT FRAMEWORK FOR TITANIUM RECYCLING: A SOUTH AFRICAN CASE STUDY

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## Abstract

South Africa has the second largest titanium ore reserves on the planet and is currently the third largest exporter of titanium-containing ore. However, none of this is converted to titanium metal commercially and much research is being done to achieve this. At present, local companies produce titanium metal products by imported titanium metal, resulting in titanium scrap creation. The majority of which is sold back to companies abroad. This paper explores the possibilities of titanium recycling, motivated by current scrap value being lost and possible future beneficiation projects. The methodology follows a sequence of understanding, development and validation. A literature study is done on possible titanium recycling routes, along with the equipment costs, throughput rates and process flows, providing an understanding of titanium recycling. A decision-making framework is developed, which takes the form of a flowchart and compiles all the recycling routes. Estimated throughput rates of each recycling method, identified in the literature study, are incorporated as decision-making criteria. This determines when a recycling route becomes feasible. Where throughput rates are unavailable, factors such as market size and selling price are used as decision criteria. The resulting framework assists with decision-making of titanium recycling, given the amount of scrap available for recycle. Financial and volumetric validation is done by break-even analysis and titanium scrap trade data interpretation. The paper concludes that titanium recycling in South Africa is not feasible beyond the scrap processing phase at present, with possible feasibility for ferrotitanium production and HDH powder production.

**Key words:** Recycling, Circular Economy, Value creation, Process chains, Titanium

## Introduction and Background

South Africa is a country with a vast array of natural resources. The majority of which is exported as raw material or developed to the lower end of the value chain. Researchers at local South African academic institutions have largely concentrated their efforts toward moving South Africa up this value chain. This includes titanium, where the government and industry have invested in various projects for beneficiation of our natural titanium resources. Some examples of strategies which are focussed on, or includes, titanium beneficiation are the Foresight Studies, the Titanium Beneficiation Initiative (TBI) and the Advanced Metals

Initiative (AMI) (Maphango, 2013; Van Vuuren, 2009). In 2014, South Africa produced 65 000 and 1 100 000 tonnes of titanium rutile and ilmenite respectively, the prior being the main raw material used in titanium metal production, making up 40% of the United States' titanium mineral imports between 2010 and 2013 (Dworzanowski, 2013; U.S. Geological Survey, 2015). However, no titanium metal is produced on a large commercial scale in the country.

This research focusses on creating value on the other end of the spectrum. Local companies, such as Aerosud and Denel, produce titanium parts for the aerospace industry. As local South African metal recyclers have little knowledge regarding the value of titanium alloys, local producers of titanium parts are forced to export titanium scrap or sell it at the lower price of general non-magnetic or non-ferrous metals. This results in South Africa losing value from its imported titanium metal goods, while providing international producers with cheap titanium feedstock material. With an all-time high of 147 431 kg titanium scrap exported in 2014, there may be many feasible options to recycle this titanium (DTI, 2015a).

The RMI Speciality Metals Complex plans to be the world's first integrated beneficiation plant, capable of beneficiating titanium, zirconium and silicon. The $1.2 billion complex is set to be commissioned by the end of 2017 and will be capable of producing 15kt/y of titanium, 2kt/y of zirconium and 1.9kt/y of silicon and its derivative products (Maphango, 2013). Planned initial outputs of titanium products include 3 kt/y sponge, 2.4kt/y ferrotitanium, 3.1 kt/y sheet, 1.6 kt/y bars, 1.6 kt/y seamless pipes and 2 kt/y slab (Primemetals, 2011). Although the majority of these products may be shipped abroad, it will inevitably boost the existing titanium product manufacturing industry in South Africa, leading to increased scrap creation and a steadier flow thereof.

Scrap metal can be classified according to source as old scrap (sourced from end-of-life products), new scrap (sourced from production processes) and home scrap (sourced from in-house production processes) (Veasey, Wilson, & Squires, 1993). This paper focusses on new scrap only, as there is no steady supply of end-of-life titanium products in South Africa and new scrap is easier to process.

## Research Methodology

The research methodology followed in this paper is seen in Figure 1. It follows a straight-forward sequence of understanding, development and validation. Understanding involves a literature study of recycling methods and a mapping of their process chains. The development of the framework follows this, which involves using the mapped process chains and data from the literature study to create a framework. This framework is then validated by break-even analysis and volumetric data.


Figure 1 Research Methodology for Titanium Recycling Management Framework

The process in developing the titanium recycling framework involves analysing all possible recycling routes. Equipment investment costs were obtained where possible, along with system throughput rates. Assuming general work hours of 8 hours per day, 20 days a month, minus 12 public holidays, yearly minimum scrap processing volumes for these steps were calculated and included in the framework. Theoretical capacity of these processes are also included, which assumes constant operating hours. This gives an idea which recycling method is best, given the amount of scrap available.

## Scrap Processing

Pre-processing is an essential part of scrap processing and adds considerable value to scrap. The processing method differs for solids (bulk-weldable and feedstock) and turnings (chips). Once scrap titanium has been sourced, it is often contaminated with cutting fluid and pieces from tungsten carbide tool tips. The standard method of processing titanium turnings involves crushing, cleaning, drying, magnetising, screening, analysing and briquetting. According to Bretherton et al. (1990) and Kaplan & Ness (1987), scrap needs to be crushed, usually by hammermill and then degreased to remove leftover cutting fluids on the chips. Crushers may be designed to perform both these tasks. Crushing the chips improves handling and their packing density during shipping. Chips are solvent-vapour degreased in trichloroethylene, which also removes some tramp impurities and foreign metal pieces. Any ferrous or ferromagnetic impurities remaining in the chips are then removed by magnetic separation. Chemical analysis is used to check for harmful contaminants and checks composition data to show levels of, for example, oxygen, iron and carbon. Figure 2 shows the process of cleaning and processing titanium machine chips.

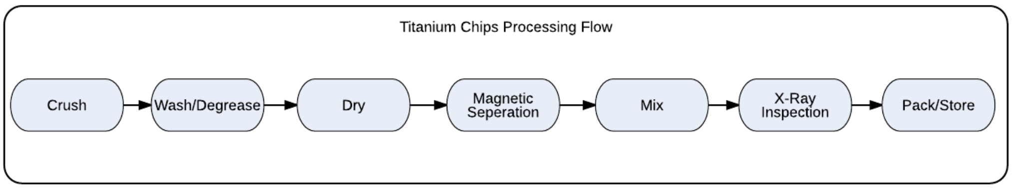


Figure 2 Titanium Chips Processing Flow (Bretherton et al., 1990; Kaplan & Ness, 1987)

Solid new scrap parts are subjected to less processing. The pieces undergo magnetic separation, is analysed with X-ray spectroscopy and segregated by grade. The remaining processing for solids is the responsibility of the melter, who may cut heavy pieces with a plasma torch, descale it by abrasion, clean it with caustic soda and pickle the surface with nitric acid containing some hydrofluoric acid. Figure 3 shows this process, with the additional steps taken by the melter to further process the scrap.

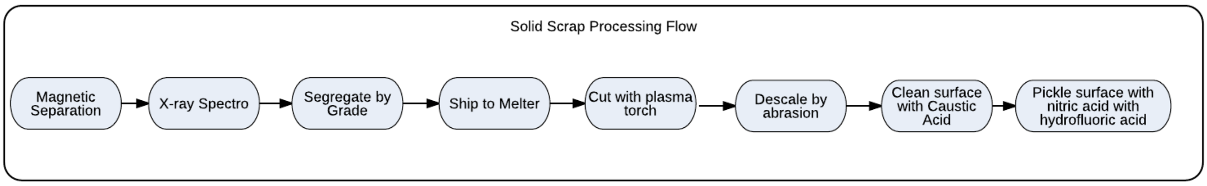


Figure 3 Titanium Solid Scrap Processing Flow (Bretherton et al., 1990; Kaplan & Ness, 1987)

A price estimate was obtained from Granroth Engineering for the equipment required to perform these pre-processing steps. The dollar equivalent is displayed in Table 1, based on the Rand to US Dollar rate of 17 February 2016. The estimated throughput of the system by Granroth is 50kg/h. At this rate, a processing plant of this size would be able to process 91200 kg of scrap per year. Theoretically, if operated for 24 hours a day, each day of the year, it could process 146 000 kg of scrap.

Table 1 Costs Associated with Titanium Scrap Processing Equipment

| *Processing Step* | *Equipment Cost ($)* |
|---|---|
| *Crusher* | 41 401 |
| *Washing* | 44 586 |
| *Drying* | 9 554 |
| *Magnetizing with Conveyed Removal* | 25 478 |
| *Screening* | 15 924 |
| *Briquetting* | 50 955 |

Unprocessed titanium scrap turnings, with a tin concentration of less than 0.5% sold for an average of $1.55/kg at the start of 2016, while aerospace quality turnings, containing a maximum of 3% oil, moisture or magnetics, was worth $4.08/kg (MetalBulletin.com, 2016; MetalPrices.com, 2016). Price estimates on clean, processed scrap is harder to obtain. Newly cleaned and sorted scrap can be sold at an improved price or be processed further, either to ferrotitanium, titanium metal or titanium powder.

## Ferrotitanium

One recycling method of titanium is to use it as alloying agent for the steel and aluminium industries. This usually takes the form of ferrotitanium or ferro-silico-titanium. In steelmaking, titanium is used for deoxidation, grain-size control, and carbon and nitrogen control and stabilization (Bedinger et al., 2013). The production of ferrotitanium is explained in Joint Research Centre (2014). The process starts with raw material in the form of lump scrap metal castings, wrought products and machine swarf. The raw material then undergoes processing, similar to that described in the Scrap Processing section. Once large pieces have been cut to size and swarf has been pulverised, degreased and dried, the titanium is weighed into pans with ferrous scrap and fed into an electric induction melting furnace. Ferrotitanium ingots are then cast and transferred to other operations for crushing, breaking, grinding, sieving and packing. Figure 4 shows the process for producing ferrotitanium, where the first three items are essentially described in more detail in the previous chapter.

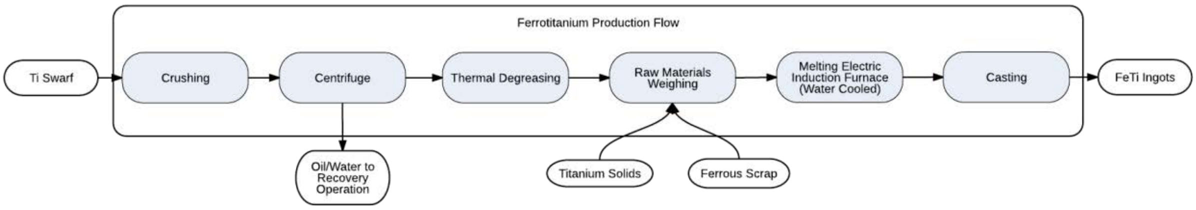


Figure 4 Ferrotitanium Production Flow (Joint Research Centre, 2014)

ASM International (1992) describes the capacity of VIM furnaces as ranging between a few kilograms and 33 tonnes. It is assumed that the throughput of ferrotitanium is limited by the processing phase, as the melting step can adapt to almost any size.

A benefit of producing ferrotitanium from titanium scrap is that lower quality scrap can be used, as the titanium is essentially downgraded to an alloying agent. Non-tin bearing ferrotitanium quality turnings sold for an average of $2.09/kg and ferrous scrap sold for 0.34$/kg in January 2015, while ferrotitanium (70% Ti) sold for $6.34/kg in the same time period (MetalPrices.com, 2016). Sources from Europe indicate that ferrotitanium of the same quality sold for between 3.85 and 4.15$/kg from December 2015 to January 2016 (MetalBulletin.com, 2016).

Currently there are no dedicated ferrotitanium production facilities in South Africa and raw materials, such as titanium, along with molybdenum and niobium are imported for the production of stainless steels (Basson, Curr, & Gericke, 2007; Mosiane, 2011; Ratshomo, 2013). As can be seen in Figure 5, a constant stream of ferrotitanium is imported to South Africa, presumably for local stainless steel production.

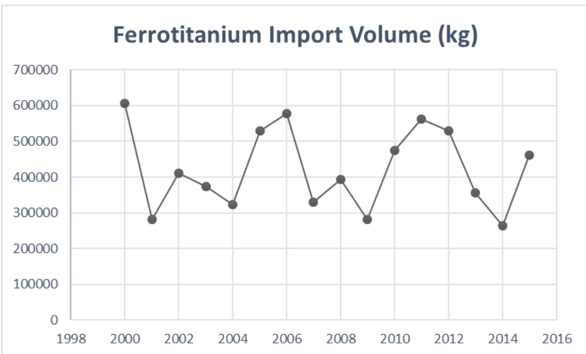


Figure 5 Ferrotitanium Import Volume (kg) (DTI, 2015b)

This recycling route seems to be a good option, given the established stainless steel industry in South Africa. The local market will result in lower logistical expenses and a consistent demand. Recycling titanium scrap to ferrotitanium does also mean that potential value is lost, as the metal is downgraded. If the RMI complex, which plans to produce 2420 tonnes of ferrotitanium per annum, is successfully introduced, it will most likely make it impossible to compete, as this amount is more than four times the amount of scrap exported in the last five years (DTI, 2015a). The increased amount of scrap generated from downstream operations from the complex may also result in cheap scrap, which might still make this a feasible solution.

## Melting

*Vacuum Arc Remelting (VAR)*

The most popular method of melting titanium and its alloys is vacuum arc remelting (VAR). VAR is used to produce high quality ingots, repeating the melt twice (2xVAR) or three times (3xVAR) to increase homogeneity and reduce gas content in the resulting ingot (Roskill Information Services, 2013).

ASM International (1992) describes VAR as a process where a titanium electrode is melted under a vacuum and the ingot solidifies in a water-cooled copper mould. Bretherton et al., (1990) describes some issues with VAR when used to recycle titanium scrap. Firstly, the method requires the production of an electrode by compacting a combination of sponge, scrap and alloying materials, and welding them together. Larger pieces of titanium can be used as an electrode. Producing these electrodes create considerable additional costs. Secondly, a refractory particle in the electrode may not be eliminated during the melting operation and may survive on the finished ingot. This means that a high density inclusion, such as a tungsten carbide tool tips, that has been compacted into the electrode may fall into the molten pool and solidify in the finished ingot. This makes it difficult to recycle scrap using VAR as it limits the quality and thus quantity of scrap that can be used.

Advantages of VAR include that it removes dissolved gasses, such as hydrogen and nitrogen, minimizes undesirable trace elements having high vapour pressures and removes oxides, improving cleanliness (ASM International, 1992). Figure 6 shows the normal process flow for a double VAR process and Table 2 shows equipment costs and maximum throughput capacity associated with a double VAR plant, used to produce titanium parts of military quality.

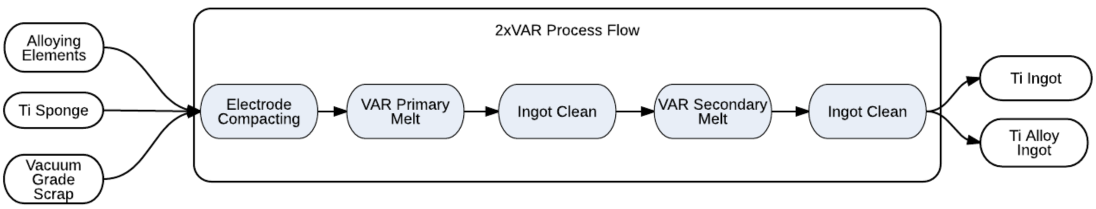


Figure 6 VAR Process Flow

*Table 2 Equipment Cost of a VAR Plant to Produce Titanium Ingots* (Sampath, 2005)

| Processing Step | Throughput (kg/h) | Equipment Cost ($) |
|---|---|---|
| Electrode Compacting | 7 000 | 5 400 000 |
| VAR Primary Melt | 400 | 7 200 000 |
| Ingot Clean | 1 000 | 540 000 |
| VAR Secondary Melt | 1 700 | 7 200 000 |
| Ingot Clean | 2 500 | 180 000 |

Assuming production occurs at the rate of the bottleneck, which is 400 kg/h for the primary melt, yearly throughput is about 729 600 kg/y. Theoretical capacity is 3 504 000 kg. Plants producing titanium melted products range between 0.6 and 50 kt/y, meaning that a production facility of this size would be at the lowest end of the scale (Roskill Information Services, 2013).

While VAR is the most widely used method to melt titanium ingots, the requirement of raw titanium sponge, which is not produced in South Africa, makes it a difficult method to recycle titanium. Only about 23 to 25% titanium scrap is used in VAR by VSMPO, Russia's leading titanium melter, which trades for $6.5/kg to over $10/kg (Roskill Information Services, 2013). Sponge traded for an average of $7.61/kg from China and $9.85/kg from Rotterdam in January 2015 (MetalPrices.com, 2016). Titanium 6Al4V ingot from the United States was worth an average of $19.01/kg between December 2014 and January 2015, while it cost $16.48/kg from Europe in the same time period.

*Cold Hearth Melting*

Cold hearth melting is an alternative to VAR, particularly applicable to scrap recycling. ASM International (1992) describes the cold hearth melting process as a two-stage process where material feeding, melting and refining takes place in a water-cooled copper trough, ladle or hearth. It then solidifies in a water-cooled copper crucible. The process allows impurities with a lower density than the molten metal to be separated by flotation and those denser than the molten material, such as pieces of tungsten carbide, to sink and be removed by sedimentation. These refining capabilities make cold hearth melting the preferred method of recycling scrap titanium. The technology is used by RMI, Timet, ATI Allvac, Toho Titanium and VSMPO-Avisma and was approved as a production method for primary structures in military aircraft in 2003 (Roskill Information Services, 2013).

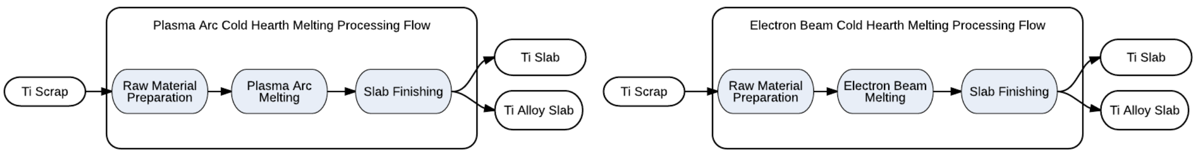


Figure 7 EB and Plasma CHM Process Flow

Cold hearth melting can be done by electron beam (EB) or plasma arc (PA). The processes are shown in Figure 7, which are the same, except for the melting stage. Table 3 and Table 4 show the estimated costs of a cold hearth melting facility, which produces titanium slab utilising plasma arc and electron beam melting technologies (Sampath, 2005).

Table 3 Equipment Cost of a Plasma Arc CHM Plant to Produce Titanium Slab (Sampath, 2005)

| Processing Step | Throughput (kg/h) | Equipment Cost ($) |
|---|---|---|
| Raw Materials Preparation | 7 000 | 5 400 000 |
| Electron Beam Melting | 450 | 14 400 000 |
| Slab Finishing | 6 000 | 180 000 |

Table 4 Equipment Cost of an Electron Beam CHM Plant to Produce Titanium Slab (Sampath, 2005)

| Processing Step | Throughput (kg/h) | Equipment Cost ($) |
|---|---|---|
| Raw Materials Preparation | 7 000 | 180 000 |
| Plasma Arc Melting | 700 | 18 000 000 |
| Slab Finishing | 6 000 | 180 000 |

Yearly throughput of PA and EB of a plant of this size is 820 800 kg/y and 1 276 800 kg/y respectively, while theoretical capacity is 3 942 000 kg/y and 6 132 000 kg/y. Both these plants are still at the lower end of the scale with regards to yearly throughput when compared on the global scale.

Cold hearth melting can be used to produce both ingots and slabs. This may result in flexibility and possible cost savings as the intermediate step of ingot production can be left out (Roskill Information Services, 2013). Titanium (of commercially pure grade 1) slab traded between $12.42/kg and $13/kg in January 2015 (MetalPrices.com, 2016). The average price of titanium melted products (ingots and slabs) was $22.75/kg in 2012 from Timet.

*Production of Mill Products*

Once titanium ingot or slab have been produced, titanium mill products can be produced to add further value to it. Fabricators receive titanium in the form of bar, plat, sheet, strip, tube, wire, wire rod, foil and extrusions. Considerable amount of capital investment is required to produce these mill products, as can be seen in Table 5. This results in a high selling price. Titanium mill products from Timet sold for an average of $54.45/kg in 2012 (Roskill Information Services, 2013).

Table 5 Equipment Cost to Process Ingot or Slab to Titanium Plate (Sampath, 2005)

| Processing Step | Throughput (kg/h) | Equipment Cost ($) |
|---|---|---|
| Beta Roll | 2 500 | 18 000 000 |

| | | |
|---|---|---|
| Alpha Beta Roll | 2 500 | 0 |
| Anneal | 7 000 | 3 600 000 |
| Flatten | 7 500 | 540 000 |
| Clean | 10 000 | 72 000 |
| Section | 25 000 | 540 000 |
| Final Inspection | 5 000 | 180 000 |

### Powder metallurgy

Titanium can be converted to powder by a number of processes. One method which uses titanium scrap will be addressed in this paper. The method is known as a hydride-dehydride (HDH) process. The HDH method takes advantage of titanium metal's high affinity for hydrogen. Titanium powder is hydrogenated by heating it in an atmosphere of hydrogen. Once the titanium has been hydrogenated, it becomes very brittle and can easily be crushed to fine powder. Afterwards, the hydrogen can be removed by heating it in a dynamic vacuum. Pure titanium is hydrogenated at ±400ºC and titanium machine turnings can be hydrogenated in about 4 hours (ASM International, 1998). This process is visually represented in Figure 8. HDH powder has been produced in South Africa on an experimental scale, some of which specifically to explore recycling of scrap turnings (Chhiba, 2012; Goso & Kale, 2010, 2011).

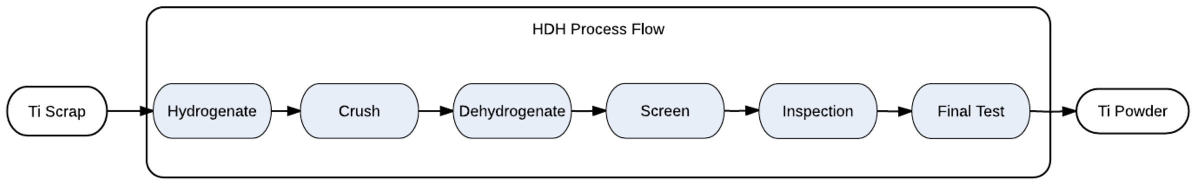


Figure 8 HDH Powder Production Process Flow (C. McCracken, 2008)

The HDH method provides a low-cost alternative titanium powder to that produced by the gas atomisation process (GA). GA powder is spherical in shape and has a narrow particle size distribution (PSD) range (the distribution the different sizes of particles). HDH powder can be screened to achieve the desired PSD and the Tekna process can be used to convert the irregular shaped HDH powder to spherical shaped powder (Froes, 2012; C. G. McCracken, Barbis, & Deeter, 2011).

### Novel and experimental processes

The IME recycling method, developed at Aachen University in Germany is a three stage process for recycling titanium metal. The method is designed specifically for low grade turnings and aims to create a closed-loop recycling process. The method involves three steps, namely conditioning, vacuum induction melting (VIM) and vacuum arc remelting (VAR). The process produces refined titanium, for applications in the automotive, healthcare or chemical industry (Friedrich, Lochbichler, & Reitz, 2007; Rotmann, Lochbichler, & Friedrich, 2011).

Some experiments have shown that recycling of titanium machine chips by severe plastic deformation may be a viable option (Luo et al., 2010, 2012; Shi, Tse, & Higginson, 2016). The process involves compressing machine chips by equal channel angular pressing (ECAP) at temperatures between 400ºC and 500ºC at pressures between 50 and 250 MPa.

## A Framework for Titanium Recycling

By organising all possible recycling routes to a single structure, the framework is created, as seen in Figure 9, which takes the form of a flowchart. Also seen in the framework are suggested volumes of scrap at which recycling via these routes becomes feasible. These volumes take the form of diamond-shaped decision-making nodes. The values are based on the minimum yearly scrap throughput of each process. Rounded white nodes represent a process termination, which in this case is represented by the end-consumer. Swimlanes are added to differentiate between sources, pre-processing, titanium melting, powder production and consumers. Shaded rounded nodes represent a product, such as titanium scrap, ingots, slabs etc. Along the bottom, an arrow is seen, which indicates that value is increased as products are processed in that order.

The value to justify the logistical costs (50kg) is based on an estimate of when recycling is done at the laboratory at Stellenbosch University. Titanium mill product production is linked only to that of CHM, since it is more cost-efficient than VAR. It is recommended that titanium mill products are produced, but with the considerable capital investment costs required, a decision-making step is included to see whether the user has sufficient capital. The production of ferrotitanium and HDH powder gives the user a choice of whether they want to further process the scrap. This is because ferrotitanium does not give a substantially higher selling price than clean titanium scrap. Further processing might be required when a larger market or a higher selling price is desired. Ferrotitanium provides this constant market, while HDH powder has a smaller market, but a high selling price.

Following the framework ensures that the most value is created from titanium scrap. A brief description is added on the right side of the model to aid management with decision-making.

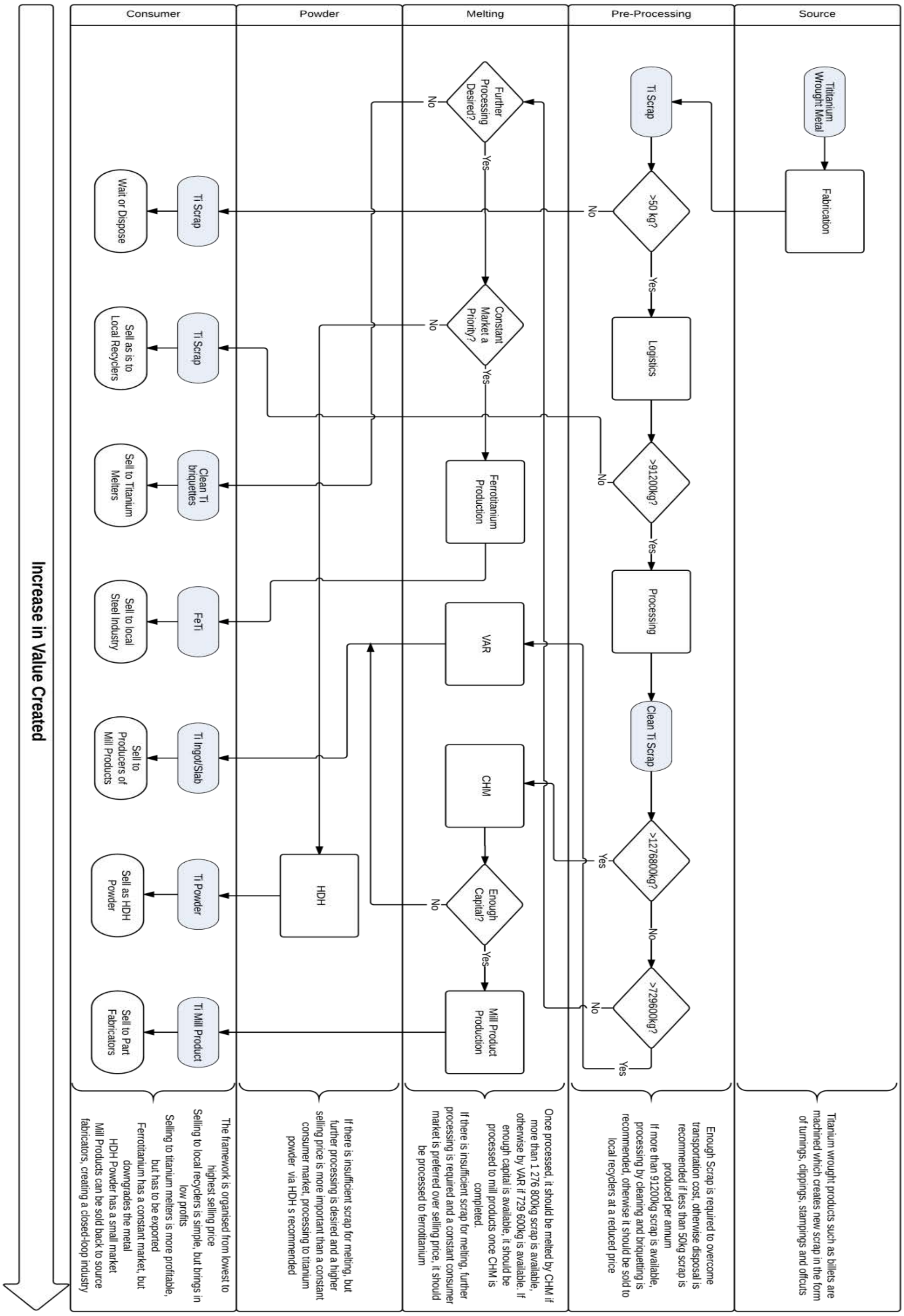


Figure 9 Titanium Metal Recycling Framework

## Validation and Discussion

Financial validation is done by a break-even analysis. This determines the amount of scrap required to break even with equipment investment costs. The amount of scrap in the country is analysed to determine whether there is a large enough volume of scrap in the country.

### Break-even Analysis

A breakeven analysis is done to determine when recycling of titanium is justified financially. Only equipment costs are taken into account for this. The following equation is used to determine the amount of scrap needed to be sold to break even.

$$x = \frac{FC}{P-V} \tag{1}$$

Where x is the break-even amount of kilogram scrap; FC is the fixed costs (in this case the equipment costs); P is the sell price per kilogram and V is the variable cost per kilogram

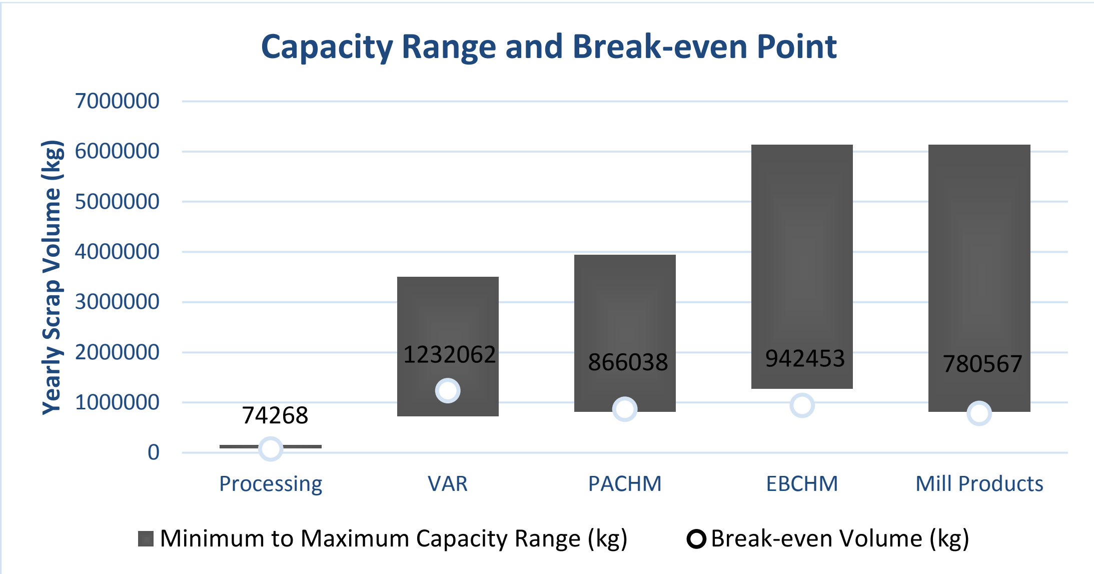


Figure 10 Minimum Capacity, Maximum Capacity and Break-even Point

Figure 10 illustrates the break-even volumes (circles), compared to the minimum and maximum yearly throughput capacities. It shows that the break-even volumes are similar to that of minimum capacity throughput for all processing methods. This means that when following the framework, which is based on minimum throughputs, equipment costs will be covered in most cases. Financial validation of the framework is thereby achieved by equipment costs. Selling prices are taken as those by Timet as described in above sections, while scrap buy cost was assumed as \$1.55/kg and clean scrap sell price as \$4.08/kg. For VAR it was assumed that 75% sponge was used, hence the higher break-even value. The figure illustrates why it is recommended that mill products be produced if there is enough capital available. The process mill products sell for a substantially higher amount, resulting in a lower break-even point than EBCHM, PACHM and VAR. It has the additional benefit of creating a closed-loop titanium industry in South Africa, allowing the recycled product to be sold back to the fabricator, from which the scrap is sourced. The figure also demonstrates the vast difference in processing and melting equipment costs.

### Available Scrap

Predicting the available scrap supply in South Africa is difficult, as can be seen in Figure 11, which shows the amount of scrap exported between 2005 and 2015. The amount of titanium scrap exported ranges from 939 kg in 2009, to 147 431kg in 2014. As there is no clear trend in South African scrap, except that it appears to spike every third year, an average is taken between 2005 and 2015. With an average yearly scrap export of 55 468.27 kg since 2005 and an estimated 74 268 kg scrap required to break even with equipment costs, equipment can be paid off in less than a year and a half, assuming average scrap availability.

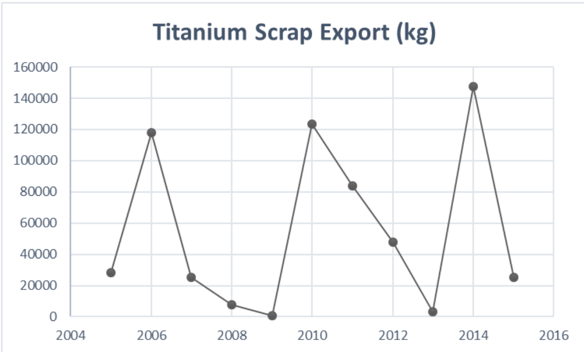


Figure 11 Titanium Scrap Metal Volume Exports From South Africa from 2005 to 2015 (DTI, 2015a)

## Conclusion and Outlook

In the current state of the South African industry, basic processing of titanium scrap metal seems to be the best option. Further processing by melting is not feasible at present, as the amount of available scrap is clearly insufficient. These options may become financially feasible if a beneficiation project like the RMI Speciality Metals Complex becomes a reality.

Future work will create a more complex economic model, including all fixed and variable costs associated with the titanium recycling process. This enable more accurate predictions and the creation of a business case for titanium recycling.

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